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EMISIONES DE CO_2 DE LA ACTIVIDAD BIOLÓGICA DE TURBERAS Y SUELOS ORGÁNICOS DE LA PATAGONIA CHILENA

CARBON EMISSION FROM BIOLOGICAL ACTIVITY OF PEATLAND AND ORGANIC SOILS OF CHILEAN PATAGONIA

Tesis para optar al grado de Magíster en Ciencias Agronómicas con Mención en Ciencias del Suelo y Recursos Naturales

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RESUMEN

Las turberas son un importante sumidero de Carbono (C), siendo este mayor a la biomasa forestal y similar a las reservas de carbón de origen fósil, sin embargo la degradación de las mismas representa una importante fuente de C. Las emisiones de gases de efecto invernadero de las turberas intervenidas no se han estudiado extensamente en la Patagonia Occidental (Chile) a pesar de la alta presión antropogénica sobre este ecosistema. El objetivo de este estudio fue evaluar la emisión anual de CO_2 de la respiración heterotrófica del suelo de turberas en condiciones no saturadas en Tierra del Fuego. Las emisiones anuales de CO_2 se midieron a partir de muestras de suelo insaturado (n=41) bajo la incubación del suelo a temperaturas locales estacionales, utilizando un analizador de gases infrarrojo no dispersivo. Los modelos espaciales para el C total del suelo y el CO_2 se calcularon usando variables discretas (C total, N total y Capacidad de Campo) y continuas (pendiente, exposición del sol, NDVI y NDWI). La media anual del CO_2 medido fue 1358 µg CO_2 g $suelo^{-1}$ y el 82% de la mineralización de C ocurrió en la estación más cálida. El CO_2 modelado en la temporada más cálida mostró niveles de CO_2 tan altos como 5 mg de CO_2 g de $suelo^{-1}$, pero el 66% del área mostró flujos entre 651 y 5.700 µg CO_2 g de $suelo^{-1}$, que corresponde a 28-92% y 9-32 % de los valores de CO_2 informados para rotaciones de cultivos. En consecuencia, después de una habilitación potencial del área de estudio para uso agrícola, las emisiones de CO_2 del suelo de la actividad heterotrófica podrían ser comparables a los sistemas de cultivo cultivable. Este ecosistema está muy expuesto a los efectos del cambio en el uso de la tierra y al aumento de la temperatura global.

Palabras clave: respiración microbiana del suelo, turberas, ecosistemas sub-antárticos, cambio de uso de la tierra, cambio climático

SUMMARY

Peatlands are important Carbon (C) reservoirs, greater than global forest biomass and similar to the coal reserves of fossil fuel, however, the degradation of them represent an important source of C.

Greenhouse gas emissions from managed peatlands have not been extensively studied in Western Patagonia (Chile) despite the high anthropogenic pressure on this ecosystem. The objective of this study was to assess the annual CO_2 emission from soil heterotrophic respiration of a peatland site under not saturated conditions at Tierra del Fuego. The annual CO_2 emissions were measured from unsaturated soil samples (n=41) under soil incubation at seasonal local temperatures, using a non-dispersive infrared gas analyzer. Spatial models for total soil C and CO_2 were calculated using discrete (total C, total N and soil field capacity) and continuous variables (slope, sun exposition, NDVI and NDWI). The annual mean of measured CO_2 was 1358 µg CO_2 g soi^{l-1} and 82% of the C mineralization occurred in the warmer season. The modelled CO_2 in the warmer season showed levels of CO_2 as high as 4 mg CO_2 g soil^{-1}, but 66% of the area showed between 600-2000 µg CO_2 g soil^{-1}, which is 28-92% and 9-32% of CO_2 values reported for crop rotations. Consequently, after a potential habilitation of the study area for agricultural use, the soil CO_2 emissions from heterotrophic activity could become comparable to arable cropped systems. This ecosystem is highly exposed to the effects of the land use change, and global temperature increase.

Key words: soil microbial respiration, bogs, sub-Antarctic ecosystems, land use change, climate change

CAPÍTULO 1

INTRODUCCIÓN

La respiración del suelo incluye la producción heterotrófica (microbiana) y autotrófica (principalmente raíz) de dióxido de carbono (CO_2), y representa el 60-90% de la respiración total del ecosistema, siendo el segundo mayor flujo de carbono en la mayoría de los ecosistemas después de la fotosíntesis (Longdoz *et al*., 2000, Shi *et al*., 2012). Aproximadamente la mitad de la respiración del suelo se deriva de la actividad metabólica del crecimiento de raíces y la asociación de micorrizas en sitios dominados por vegetación forestal, mientras que los valores de respiración del suelo para sitios de vegetación no forestal son menores (37%), debido a que el componente autotrófico es menos dominante en estos ecosistemas (Hanson *et al*., 2000). Por lo tanto, en ecosistemas distintos de los bosques, la producción de CO_2 del suelo depende en gran medida de la actividad microbiana del suelo, *i.e*. mineralización de Carbono (C).

En los ecosistemas terrestres, los suelos contienen más C que la vegetación y la atmósfera (Swift, 2001) y un pequeño incremento en la respiración del suelo o cambios en los factores que controlan la velocidad del proceso pueden provocar cambios significativos en la concentración atmosférica de CO_2 (Schlesinger y Andrews 2000, Veenendaal *et al.*, 2004, Kane *et al.*, 2005, Dias *et al*., 2010; Murcia-Rodríguez *et al*., 2012). La mayor concentración global de C se encuentra en las zonas húmedas y frías en el hemisferio norte, dominadas por acumulaciones profundas de turba y suelos permafrost (Tarnocai *et al*., 2009).

Las turberas contienen los mayores depósitos terrestres de C, desempeñando un papel importante como sumidero de CO_2 atmosférico y fuente de metano (CH_4) (Frolking et al., 2011), que afectan al ciclo global del C (Wisser *et al*., 2011). Aunque estos ecosistemas responden lentamente a los aumentos de la temperatura del aire debido a las propiedades aislantes de la turba (Rahn *et al*., 2012), el cambio de las condiciones ambientales que probablemente ocurra debido al cambio de uso de la tierra y al cambio climático podría afectar los intercambios de CO_2 (Limpens *et al*., 2008) y por lo tanto reducir la eficiencia de las turberas como sumideros del suelo C, contribuyendo así, a la futura carga atmosférica de gases de efecto invernadero (Frolking *et al*., 2011).

Existe un creciente interés de habilitar turberas a través de drenaje, para cambiar el uso de la tierra a sistemas forestales, agrícolas o pastizales (Kandel *et al*., 2018), con consecuencias ambientales aún inciertas, ya que se modifica la velocidad de difusión de oxígeno en el suelo, acelerando de esta manera, la descomposición aeróbica de la materia orgánica, con mayores emisiones de CO_2 (Veber *et al.*, 2018). Las reservas de C en el suelo, que son resistentes a la descomposición en condiciones anaeróbicas, que prevalecen en estos suelos, pueden perderse mediante la respiración aeróbica después del drenaje (Minkkinen y Laine, 1998).

Debido a que la emisión de CO_2 es un subproducto de la respiración microbiana bajo condiciones oxidativas del suelo y un gas de efecto invernadero, la cuantificación de la respiración microbiana es esencial para comprender el efecto del drenaje de turberas en ecosistemas como los de la Patagonia, donde existe limitada investigación y un creciente interés en transformar este ecosistema en sistemas agrícolas.

La mayoría de los estudios sobre ecosistemas de turberas se centran principalmente en las emisiones de CO_2, CH_4 y N_2O debido a su efecto sobre el cambio climático global (Kandel *et al*, 2018) y se basan en pocas mediciones debido a las dificultades de utilizar cámaras de intercambio de gas (Veber *et al*., 2018). Por lo tanto, los valores de emisiones de CO_2 de turberas en la región de la Patagonia han sido reportados en condiciones naturales para diferentes regímenes de precipitación que van de 420 a 1.500 mm año^{-1} (Broder *et al.*, 2015, Peri *et al*. 2015, Veber *et al*. 2018) y como una comparación entre las turberas naturales (2.4 a 0.64 g CO_2 m^{-2} d^{-1}) e intervenidas con distintas intensidades (3.8 a 0.96 g CO_2 m^{-2} d^{-1}) (Broder *et al*., 2015, Peri *et al*., 2015, Veber *et al*., 2018).

Sin embargo, la metodología estándar aplicada para estudiar las emisiones de gases no considera la variabilidad espacial (Webster y Oliver, 2007) de la materia orgánica del suelo y sus procesos asociados, que pueden ser importantes en los ecosistemas de turberas debido a la variabilidad en las condiciones de formación, el tipo de vegetación, la dinámica de los niveles de agua subterránea, la labilidad del C del suelo y el perfil microbiano del suelo (Kim *et al*, 2016). Un enfoque basado en el análisis espacial del muestreo distribuido espacialmente se puede utilizar para estimar y modelar mejor, por ejemplo, las contribuciones potenciales de las emisiones de CO_2 de la respiración microbiana del suelo de las turberas. Esta es una herramienta útil que asegura una mejor comprensión de un proceso biológico variable como la respiración microbiana y, por lo tanto, la producción de CO_2 asociada, en la región Patagónica.

Particularmente, estudios experimentales sobre la respiración del suelo en todo el mundo han indicado una gran heterogeneidad espacial de la respiración microbiana y, por lo tanto, de las emisiones de CO_2. Zhou, *et al*., (2009) y Xu *et al*., (2015), han destacado que la variabilidad espacial es crucial para proyectar las emisiones de CO_2 futuras.

Las turberas patagónicas constituyen el principal sumidero y reserva de C en el hemisferio sur extratropical (Iturraspe, 2016) funcionando de manera similar a las turberas del norte, aunque se han desarrollado bajo diferentes condiciones climáticas (Loisel y Yu, 2013). Comparativamente, las condiciones climáticas del hemisferio sur presentan temperaturas estacionales más bajas y mayores rangos de precipitación anual y humedad relativa, que las turberas en el hemisferio norte (Loisel y Yu, 2013). Por lo tanto, el estudio de estos ecosistemas ayudará a la compresión de los niveles de emisiones de CO_2 de suelos con acumulaciones de turba creados bajo diferentes condiciones climáticas.

En particular, las turberas en la región de la Patagonia cubren aproximadamente 45.000 km^2 (Yu *et al*., 2010) y están dominadas por clima polar y templado (Sarricolea *et al.*, 2016). Los suelos de este ecosistema en la región occidental de la Patagonia (Chile) han sido señalados como ecosistemas frágiles i) a la descomposición de carbono orgánico debido a las grandes reservas de C orgánico del suelo susceptibles de ser mineralizadas bajo el calentamiento global, ii) a la alta presión antropogénica debido al manejo para la obtención de productos de invernadero, y iii) para el cambio de uso de la tierra a las praderas para pastoreo, mediante el drenaje de los sistemas (Córdova *et al*., sin publicar).

Investigaciones recientes sobre ecosistemas fríos de la Región Patagónica han sido publicadas para las islas Antárticas por Thomazini *et al.*, (2014) y Thomazini *et al.*, (2016), relacionadas con la emisión de CO_2 y relación de CO_2-C en los ecosistemas de la Patagonia, abordando la variabilidad geoespacial del intercambio CO_2-C del suelo en la Antártida marítima, sin embargo, no existen este tipo de estudios en la zona continental de la Patagonia Chilena debido principalmente a la dificultad para acceder a estas áreas remotas (Iturraspe, 2016). La cuantificación del CO_2-C en la Patagonia occidental de Chile, considerando la variabilidad espacial del suelo, es el punto de partida para la predicción de estos ecosistemas frágiles como reservorios y fuentes de C.

HIPÓTESIS

Las emisiones de CO_2 de la respiración heterotrófica en suelos orgánicos y turberas de ecosistemas sub antárticos aumenta al habilitar turberas para uso agrícola, en la región Patagónica (Chile), debido al alto contenido de C de suelo expuesto a condiciones aeróbicas.

OBJETIVO GENERAL

Evaluar la contribución de CO_2 a la atmósfera de una turbera drenada producto de la respiración microbiana en Tierra del Fuego, considerando la variabilidad espacial del suelo.

OBJETIVOS ESPECÍFICOS

- Determinar la respiración anual heterotrófica de suelos de Tierra del Fuego a escala de sitio.
- Evaluar la variación estacional de la respiración microbiana de suelos orgánicos y turberas de ecosistemas fríos de la Patagonia Chilena.
- Evaluar estacional y espacialmente la razón CO_2-C total (µg CO_2 C mg^{-1}) en suelos orgánicos y turberas de la Patagonia Chilena.

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CAPÍTULO 2

CARBON DIOXIDE EMISSIONS LINKED TO SOIL HETEROTROPHIC ACTIVITY FROM A SIMULATED DRAINED PEATLAND IN WESTERN PATAGONIA (TIERRA DEL FUEGO, CHILE)

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ABSTRACT

Greenhouse gas emissions from managed peatlands have not been extensively studied in Western Patagonia (Chile) despite the high anthropogenic pressure on this ecosystem. The objective of this study was to assess the annual CO_2 emission from soil heterotrophic respiration of a peatland site under not saturated conditions at Tierra del Fuego. The annual CO_2 emissions were measured from unsaturated soil samples (n=41) under soil incubation at seasonal local temperatures, using a non-dispersive infrared gas analyzer. Spatial models for total soil C and CO_2 were calculated using discrete (total C, total N and soil field capacity) and continuous variables (slope, sun exposition, NDVI and NDWI). The annual mean of measured CO_2 was 1358 µg CO_2 g soi^{l-1} and 82% of the C mineralization occurred in the warmer season. The modelled CO_2 in the warmer season showed levels of CO_2 as high as 4 mg CO_2 g soil^{-1}, but 66% of the area showed between 600-2000 µg CO_2 g soil^{-1}, which is 28-92% and 9-32% of CO_2 values reported for crop rotations. Consequently, after a potential habilitation of the study area for agricultural use, the soil CO_2 emissions from heterotrophic activity could become comparable to arable cropped systems. This ecosystem is highly exposed to the effects of the land use change, and global temperature increase.

Key words: soil microbial respiration, bogs, sub-Antarctic ecosystems, land use change, climate change

INTRODUCTION

Soil respiration -encompassing heterotrophic (microbial) and autotrophic (root) production of C dioxide (CO_2), accounts for 60-90% of the total ecosystem respiration, which is the second largest carbon (C) flux in most ecosystems, after the photosynthesis process (Longdoz *et al*., 2000, Shi *et al*., 2012). Approximately half of soil respiration is derived from metabolic activity of root growth and mycorrhizae association in sites dominated by forest vegetation, whilst values of soil respiration for the non-forest vegetation are lower (37%), because the autotrophic component is less dominant in these ecosystems (Hanson *et al*., 2000). Thus, in ecosystems others than forests, the soil CO_2 production is highly dependent on soil microbial activity, i.e. C mineralization.

In terrestrial ecosystems, soils contain more C than the vegetation and the atmosphere together (Swift, 2001), and a small increment in soil respiration or change in the factors controlling the rate of the process can result in significant changes in the atmospheric CO_2 concentration (Schlesinger and Andrews 2000, Veenendaal *et al*., 2004, Kane *et al*., 2005, Dias *et al*., 2010; Murcia-Rodríguez *et al*., 2012). The largest global C concentration can be found in wet and cool weather areas in the northern hemisphere, dominated by deep accumulations of peat and permafrost soils (Tarnocai *et al*., 2009). Peatlands contain the largest terrestrial C pools, playing an important role as sink of atmospheric CO_2 and source of methane (Frolking *et al*., 2011), affecting the global cycle of C (Wisser *et al*., 2011). Although this ecosystem responds slowly to increases in air temperature, due to the insulating properties of the peat (Rahn *et al*., 2012), the change of environmental conditions, likely to occur due to land use change and climate change, could potentially affect the exchanges of CO_2 (Limpens *et al.,* 2008), and thereby reduce the efficiency of peatlands as soil C sinks, contributing to the future atmospheric burden of greenhouse gases (Frolking *et al*., 2011).

There is an increasing interest in draining peatlands to change the land use to forestry, agriculture or pasture systems (Kandel *et al*., 2018), with environmental consequences, as the rate of oxygen diffusion in the soil is modified, accelerating aerobic decomposition of the organic matter, with increased CO_2 emissions (Veber *et al*, 2017). Soil C stocks, which are resistant to decomposition under anaerobic conditions, prevalent in wetland soils, can be lost by aerobic respiration after drainage (Minkkinen and Laine, 1998).

Because the emission of CO_2 is a byproduct of the microbial respiration under oxidative conditions of the soil, and a greenhouse gas, quantifying microbial respiration is essential to understand the effect of draining peatlands in ecosystems like the ones in the Patagonia region, where there is limited research carried out on this ecosystem, and an increasing interest in transforming this ecosystem into agricultural land.

Most of the studies on peatlands ecosystems are mostly focus on emissions of CO_2, CH_4, and N_2O due to their effect on global climate change (Kandel *et al*., 2018), and they are based on scarce measurements because of the practicality of using gas interchange chambers (Veber *et al*., 2018). Thus, values of peatland C emissions in the Patagonia region have been reported under natural conditions for different precipitation regimes, from 420 to 1,500 mm yr^{-1} (Broder *et al*., 2015, Peri *et al*, 2015, Veber *et al*., 2018), and as a comparison between natural (2.4 to 0.64 CO2 g $m^{-2}d^{-1}$) and managed peatlands (3.8 to 0.96 g $m^{-2}d^{-1}$) (Broder *et al.*, 2015, Peri *et al.*, 2015, Veber *et al*., 2018). However, the standard methodology applied to study gas emissions enforces to overlook the spatial variability (Webster and Oliver, 2007) of the soil organic matter and its associated processes, which can be of importance in peatland ecosystems because of the variability on the formation conditions, the type of vegetation, dynamic of the groundwater levels, lability of soil C, and the microbial soil profile (Kim *et al*, 2016). Therefore, an approach based on spatial analysis from spatially distributed sampling can be used to better estimate and model for example potential contributions of CO_2 emissions from soil microbial respiration from peatlands. This is a useful tool that ensures a better understanding of a variable biological process, such as microbial respiration, and so the CO_2 production associated in the Patagonia Region.

Particularly, experimental studies on soil respiration around the globe have indicated high spatial heterogeneity of microbial respiration, and therefore CO_2 emissions. Zhou *et al*. (2009) and Xu *et al*. (2015) have also highlighted the role of the spatial variability as crucial for projecting future climate change and CO_2 emissions.

The Patagonian peatlands constitute the main C sink and C storage in the extratropical southern hemisphere (Iturraspe, 2016) functioning similarly to that of northern peatlands, although they have been developed under different climate boundary conditions (Loisel and Yu, 2013). Comparatively, the conditions in the south hemisphere environment have distinctive lower seasonal temperature values, wider ranges of annual precipitation and relative humidity, than the peatlands in the north hemisphere (Loisel and Yu, 2013). In particular peatlands in the Patagonia region cover about 45,000 km^2 (Yu *et al.*, 2010) and are dominated by polar and temperate climate (Sarricolea *et al*., 2016). The soils from this ecosystem in the Western Patagonia (Chile) region have been pointed out as fragile ecosystems i) to organic carbon decomposition due to the large stocks of soil organic C susceptible to be mineralized under global warming, ii) to the high anthropogenic pressure for management to obtain greenhouse products, and iii) to the land use change to prairies for grazing, by draining the systems (Córdova *et al.*, unpublished).

The objective of this study was to evaluate the CO_2 contribution to the atmosphere at the site scale from microbial respiration under simulated drained soil condition in Western Patagonia region (Tierra del Fuego, Chile), considering soil spatial variability. This can support the hypothesis of soil CO_2 increase from peat conversion to agricultural systems, filling the gaps regarding carbon emissions from peatland under new scenarios of management.

MATERIALS AND METHODS

Experimental site

The experiment was carried out on soil samples taken from "Tierra del Fuego" located in the Western Patagonia (53°59′64″ S, 69°18′19″ W). The specific sampling area comprised 294 Km^2 (Figure 1) and has been temperature-modelled by Hijmans *et al*., (2005) as the coldest zone in Chilean Patagonia, were surface mean temperature range from -6°C in July to 16°C in December, according MODIS/Terra Land Surface Temperature (Zhengming *et al*., 2015). The climate in this area varies from cold temperate with high relative humidity, to trans-Andean climate with steppe degeneration. The mean annual precipitation is 437 mm (Dirección General de Aguas, 2017) and the mean elevation of the site is 259 m a.s.l.

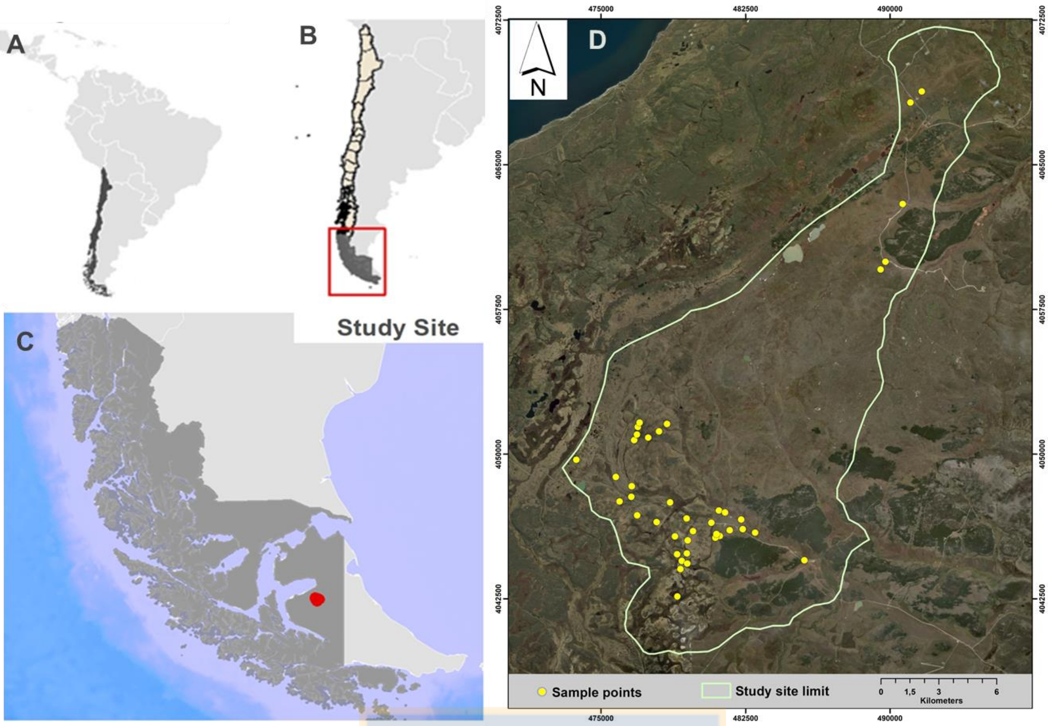

Figure 1. Location of the experimental site. Regional location (A). National location (B). Sub national location (C). Site and spatial distribution of the sample points (D). (Source: Elaborated with own data and satellite images from Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community).

The peatland in the experimental site corresponds mainly to *Sphagnum moss* forming blanket bogs, and other species, such as *Deschampsia cespitosa* (L.) P. Beauv., *Deschampsia airiformis* (Steud.) Benth. & Hook. F., *Festuca pallescens* (St.-Yves) Parodi, *Phleum alpinum* L., *Poa pratensis* L., *Trisetum spicatum* (L.) K. Richt. var. cumingii (Nees ex Steud.) Finot, *Elymus magellanicus* (E. Desv.) A. Löve, *Festuca sp*., *Phleum alpinum* L., *Caltha sagittata* Cav., *Hordeum fuegianum* Bothmer N. Jacobsen & R.S. Jorg., *Trisetum spicatum* (L.) K. Richt. var. cumingii (Nees ex Steud.) Finot, *Apera interrupta* (L.) P. Beauv., and *Rumex acetosella* L. The vegetation is particularly grazed by native *Lama guanicoe*.

The level of the groundwater at the time of sampling was found at 35 cm from the soil surface, although at some areas the level reached the surface. The first 0-10 cm of the soil randomly sampled showed low pH (5.2) and low levels of available nitrogen (1.3 mg kg^{-1} NO_3^- and 2.8 mg kg^{-1} NH_4^+), phosphorous (P-Olsen 3.9 mg kg^{-1}), sulphur (9.8 mg kg^{-1} SO_4^{-2}), and potassium (118.8 mg kg^{-1} available K), and low total exchangeable bases content (1.2 cmol kg^{-1}). The soil sublayer (10-35 cm) sampled showed slightly higher pH (5.5) but lower values for the other chemical properties: available nitrogen (0.9 mg kg^{-1} NO_3^- and 0.9 mg kg-1 NH_4^+), phosphorous (P-Olsen 1.5 mg kg^{-1}), sulphur (5.8 mg kg^{-1} SO_4^{-2}), potassium (44.9 mg kg^{-1} available K), and total exchangeable bases content (0.82 cmol kg^{-1}).

Soil sampling

A two-dimension spatial soil sampling was carried out at end of the summer season, over the described area (Figure 1) at irregular sampling intervals, between 200-500 m. Soil samples (n=41) were collected at 0-20 cm depth identifying geographical position and the altitude attribute. The number of samples was limited due to the terrain conditions (relief and small streams), therefore, there was a reduced possibility of using vehicle across the sampling area. The soil samples were obtained within two days in order to maintain original conditions in all of them. After that, the samples were transported and stored at 4°C until analysis (six weeks).

Soil analysis and treatment application

Soil samples were partially air-dried to release the excess of water and facilitate the sieving, done using a 2 mm sieve. Biological mineralization of C (soil incubation) and total soil C (dry combustion, Wright and Bailey, 2001) were measured at each sampling point in order to quantify the CO_2 contribution from the soil, and to estimate the C cycling state in this site. Additionally, physical analysis of soil samples included field capacity and wilting point measurements (Meyer and Gee, 1999), bulk density of disturbed samples (Blake and Hartge, 1986), and soil colloid content using the hydrometer method (Gee and Bauder, 1986). The field capacity and bulk density parameters were used to adjust the soil moisture of the samples up to field capacity point before incubation, as a simulated drained condition of the soil. The samples were kept at field capacity point during the incubation period, verifying the moisture every 15 days and replenishing any loss of water to ensure the samples contained the maximum water they could hold.

Microbial respiration analysis

The CO_2 emission from the soil microbial respiration activity was measured in the laboratory by the incubation of 10 g of soil in a 50 ml falcon tube with a rubber septa cap (n=41). The incubation systems were weighted and securely sealed with parafilm to avoid ambient CO_2 fluxes, and kept in an incubation camera at specific temperatures (Table 1) to simulate the actual surface temperature conditions of the study site during a year. To obtain the mean monthly surface temperature of the study site, MODIS/Terra Land Surface Temperature historic series (2000 – 2012) were used.

Table 1. Experimental surface temperatures used for incubation assays of soil samples collected in a peatland site from Western Patagonia (Chile). (Source: Elaborated with MODIS/Terra Land Surface Temperature historic series, 2000-2012).

Season	Month	Temperature (°C) [&]
	January	14
Summer (warm season)	February	13
	March	9
	April	4
Autumn (cold season)	May	0
	June	-3
	July	-6
Winter (cold season)	August	0
	September	5
	October	10
Spring (warm season)	November	15
	December	16

[&] Mean monthly temperatures

The CO_2 evolution was determined with a single path, dual wavelength, non-dispersive infrared (NDIR) gas analyzer (LI-820) by extracting 1 ml gas from the incubation system at room temperature (30 min at 20°C) with a precision sampling syringe and injecting into the CO_2 analyzer every 15 days to measure the concentration (ppm) of CO_2, and then calculated as µg CO_2 g soil^{-1}.

Analysis of site variables

Remote sensing was used for detecting and mapping regional landscape patterns and processes at the experimental study area. The landscape morphology was described through a Digital Elevation Model (DEM) to assess the slope, the altitude and the sun exposition of each sampling point. To assess the vegetation cover and soil moisture at the study area the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Water Index (NDWI) were used derived from Landsat tiles with a spatial resolution of 30 m (Landsat 8).

A trend analysis was explored by applying linear regression between the variables, soil total C, soil total N, C/N ratio, colloid percent, bulk density, field capacity, NDVI, NDWI, altitude, sunlight exposure and slope, and CO_2 evolution. A correlation matrix was used to determine the variables that were highly correlated ($p < 0.001$). In the same way, variables such slope, altitude, sunlight exposure, NDVI, NDWI, and soil total N were used for the spatial analysis and interpolation of the soil total C within the sampled area.

The CO_2 emission from soil microbial C decomposition in the study site was modelled using the geostatistics application available in the Arc-GIS package (ArcGIS 10.3). All maps were modelled through interpolation using co-kriging procedure for the variables highly correlated with soil total C and CO_2 production (Table 4), to improve the interpolation (Knotters *et al*., 1995) for the estimation of the spatial distribution of CO_2 emissions.

RESULTS AND DISCUSSION

Soil C and C mineralization of simulated drained peatland in Western Patagonia (Chile)

The study site showed a large mean value of soil total C, although the range for this variable was 488 mg C g soil^{-1} and 75% of the measured values were < 170 mg C g soil^{-1} (Table 2). Since the soil layer sampled was 0-20 cm depth excluding the organic peat material, the soil contains higher total C level compared to agricultural systems, which can be a desirable condition to convert this type of land to a managed crop, pasture, or grassland system. The site also shows the potential for storing C in the soil, and C to N ratio of 17, as described for peatlands (Joosten, 2010). Consequently, an initial responsive reaction towards biological oxidation of C and CO_2 emission under land use change might be expected, assuming that most of the soil C in this type of ecosystem might be organic.

A net CO_2 emission from drained peatlands is foreseen (Frolking et al., 2011), and at the study site the measured annual CO_2 emission from the heterotrophic soil microbial activity, adjusted to field capacity moisture content, was 1358 µg CO_2 g soil^{-1} (Table 2).

Table 2. Summary statistics of soil organic matter and C mineralization from a simulated drained peatland in Western Patagonia (Chile). Annual and seasonal values of CO_2 from microbial activity were measured under controlled laboratory conditions. (Source: Elaborated with own data).

	Soil			Heterotrophic activity			
	Total C (mg g soil^{-1})	N total (mg g soil^{-1})	C/N	C mineralization (µg CO_2 g soil^{-1})			Soil CH_4 (µg CH_4 g soil^{-1} 30 days^{-1})
				CO_2 year^{-1}	CO_2 warmer[&] season^{-1}	CO_2 colder[&&] season^{-1}	CH_4 warmer[&] season^{-1}
Number of data	41	41	41	41	41	41	10
Mean	169.6	9.5	17.2	1357.9	1109.7	248.3	0.002
Median	140.0	8.2	16.6	1130.2	883.0	224.8	0.000
St. Error	16.5	0.7	0.5	143.9	128.6	23.5	0.001
St. Deviation	105.7	4.2	3.0	916.4	822.2	148.6	0.002
Minimum	68.4	4.7	13.4	261.2	197.1	60.6	0.000
Maximum	556.0	23.8	25.9	5410.8	4921.2	667.0	0.007
Variance	1117.1	1.8	8.7	839761.6	676042.8	22093.4	0.000
Coef. variation	631.7	462.7	16.9	69.2	75.7	62.0	128.5
Skewness	23.6	18.8	1.1	2.3	2.7	0.9	0.81
Kurtosis	56.3	37.6	0.8	8.7	11.1	0.4	-1.19
25th percentile	117.0	7.0	14.8	712.1	542.2	122.2	0.000
75th percentile	170.0	10.0	18.4	1774.8	1378.1	300.0	0.004

[&] Temperature range of soil incubation: 9 ºC to 16 ºC, representing October-March period.

[&&] Temperature range of soil incubation: -6ºC to 5ºC, representing April-September period.

The mean value is low compared to the ranges informed by Zagal *et al*. (2002) and Zagal and Córdova (2005) for arable crop rotations, measured within 30 and 10 days, respectively; however, the soil incubation temperature of the previous report was 22°C, which allows the optimal microbial activity for C mineralization. In the site under study, the incubation temperature was matched with the local conditions, and at the best, the warmest season reaches up to 16°C (Table 1) which restricts the activity of soil microorganisms. Differences in the CO_2 emission from peatlands and ordinary agricultural soils might also reside in the diversity of microbial community developed under the correspondent ecosystems (Brouns *et al.*, 2016).

As the total soil C values, the mineralized C showed a large variability, represented by coefficient of variation over to 62% (Table 2). The annual site CO_2 emission is the result of the C mineralization from every month (Figure 2), that shows a positive response of microbial activity to the increase of temperature (R^2=0.9) (Figure 3), as it has been reported before by Tang et al., (2003) and Lund *et al*. (2010).

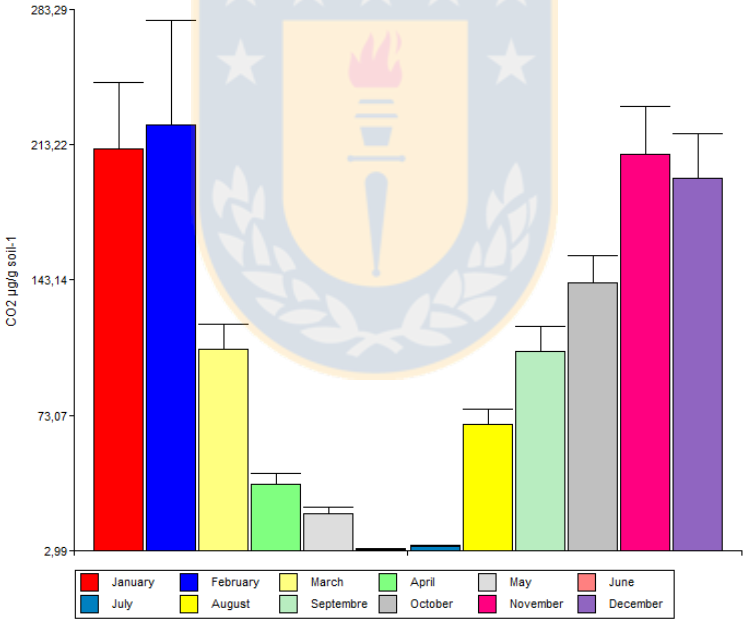

Figure 2. Monthly mean CO_2 emissions (µg CO_2 g soil^{-1}) ± SE (n=41) from soil heterotrophic respiration from a simulated drained peatland in Western Patagonia (Chile). (Source: Elaborated with own data).

The soil heterotrophic respiration observed here showed a lineal function (Figure 3) rather than an exponential function described by Lloyd and Taylor (1994), Fang and Moncrieff (2001), Murcia-Rodríguez *et al.*, (2012).

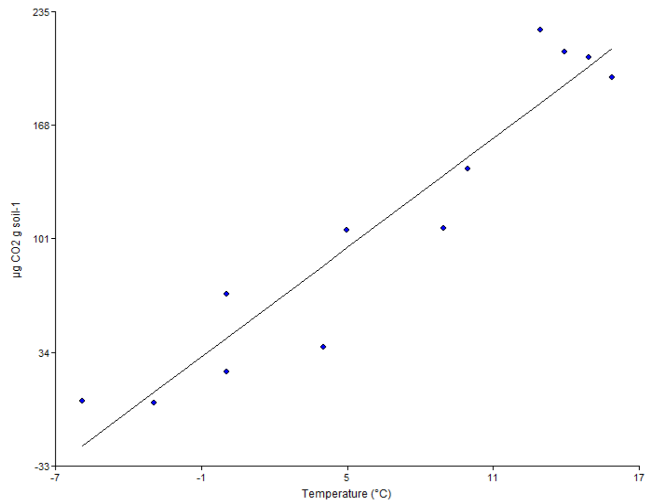

Figure 3. Relationship between seasonal temperatures and C mineralization from soil heterotrophic respiration using data from a simulated drained peatland in Western Patagonia (Chile). $y=10.67x +42.34$, $R^2= 0.91$, $p<0.0001$. (Source: Elaborated with own data).

The mean monthly CO_2 emission is minimum in June (4 µg CO_2 g soil^{-1}) and maximum in February (224 µg CO_2 g soil^{-1}) (Figure 2), and the total CO_2 emission from soil heterotrophic respiration was 1358 µg CO_2 g soil^{-1} (Table 2). According to the level of C mineralization for CO_2 production, higher and lower classes were defined as the warmer and colder seasons (Table 2). Thus, the larger contribution to the annual CO_2 emission from the study site occurred during the period October to March (1110 µg CO_2 g soil^{-1}), which accounted for 82% of the C emission during the year (Table 2). The CO_2 measured during the so-called warm season is 4.5 times larger than the one registered in the cold season, but the data dispersion is narrower as the temperatures are the lowest; this is, in the warm season the maximum measured value is 25 times the lowest value, whilst this difference is only over 10 fold increase for the cold season (Table 2). Thus, the warm season dispersion explains the variability of the annual CO_2 emission data, showing a range (maximum minus minimum value) of 5150 µg CO_2 g soil^{-1}.

As a consequence of draining peatland site for agricultural preparation, the methane emissions are reduced. The results from a random data subsample in this study showed negligible values (Table 2) as it has been also reported for drained bogs (Kandel *et al.*, 2018), which demonstrates the efficacy of the moisture treatment applied to the soil samples to simulate a drained condition.

Spatial analysis of soil CO_2 emissions from simulated drained peatland.

Modelling total soil carbon for the study area

Total soil C showed large variability of values at the study area, and the measured data did not follow a normal distribution (Table 2), but they were "log-transformed" for the spatial interpolation. The range difference between total C and N decreased as total C > total N > C:N ratio (Table 2), and therefore it was plausible to use total N as an auxiliary variable to improve the model estimation of the total C for the study area. Simple correlation between total C and total N was significant as well as total C and soil field capacity (Table 3), and therefore they were introduced in the modelling procedure to estimate the total soil C. The soil field capacity variable appears convenient to use, as this represents the applied drainage condition of the peatland site studied here.

Table 3. Pearson coefficient for simple correlations between soil discrete and continuous variables measured and collected for the peatland (Western Patagonia, Chile) for total soil carbon and heterotrophic respiration CO_2. (Source: Elaborated with own data).

		Heterotrophic soil respiration (µg CO_2 g soil^{-1})		
Variables	C total	Annual	Warmer season$^{\&}$	Colder season$^{\&\&}$
Available soil moisture	0.71***	0.40 ns	0.36 ns	0.46*
Soil field capacity	0.71***	0.40*	0.37ns	0.47*
Permanent wilting point	0.72***	0.41*	0.37 ns	0.47*
Total N	0.95***	0.57***	0.56**	0.46*
C:N ratio	0.74***	0.45***	0.47**	0.19 ns
Colloids	-0.26***	-0.06 ns	-0.11 ns	0.22 ns
Total C	1.00 ***	0.61***	0.61***	0.41*
Sunlight Exposure	0.23 ns	0.03 ns	0.04 ns	-0.05 ns
Slope	-0.32 ns	-0.28 ns	-0.28 ns	-0.21 ns
NDVI	0.10 ns	-0.02 ns	-0.04 ns	0.11 ns
NDWI	0.22 ns	0.05 ns	0.05 ns	0.05 ns
Altitude	0.09 ns	0.03 ns	-0.06 ns	0.12 ns

*p < 0.01; ** p < 0.001; *** p < 0.0001; ns: non-statistical significance (p > 0.01).
$^{\&}$ Temperature range of soil incubation: 9 ºC to 16 ºC, representing October-March period.
$^{\&\&}$ Temperature range of soil incubation: -6ºC to 5ºC, representing April-September period.

The relationship between total soil C and continuous variables such as altitude, slope, sunlight exposure, NDVI, were tested as continuous and discrete variables. This was done to improve the model estimations of soil C for the study site, due to their contribution to explain the primary site productivity (NDVI) and soil organic matter decay conditions through temperature and moisture (slope, altitude, sunlight exposure, NDWI). The correlation between these variables and total soil C was not significant (Table 3); however, some of them proved to improve the model estimations (Table 4).

Table 4. Model estimations for total soil C and annual and seasonal CO_2 heterotrophic respiration from a simulated drained peatland in Western Patagonia (Chile). (Source: Elaborated with own data)

Variables of soil carbon models	Average standard error	Percent error
Total soil C models		
N Total	28.6548	17.1%
N Total + NDVI	27.3053	16.3%
N Total + NDWI	25.9619	15.5%
N Total + Soil Field Capacity + Altitude -DV	24.2207	14.5%
N Total + Soil Field Capacity	23.2816	13.9%
N Total + Soil Field Capacity + NDVI	22.6196	13.5%
N Total + Soil Field Capacity + NDVI-DV	22.6140	13.5%
N Total + Soil Field Capacity + Sunlight exposure	21.8661	13.1%
N Total + Soil Field Capacity + NDWI	21.7066	13.0%
N Total + Soil Field Capacity + Slope	**21.5377**	**12.9%**
Annual CO_2 models		
C Total + Soil Field Capacity + Sunlight exposure	996.0183	74.8%
C Total + Soil Field Capacity + NDVI-DV	992.0582	74.5%
C Total + Soil Field Capacity + Altitude-DV	975.2388	73.3%
C Total + Soil Field Capacity + slope	897.7826	67.5%
C Total + Soil Field Capacity + NDWI	923.5767	69.4%
C Total + Soil Field Capacity + slope-DV	888.5875	66.8%
C Total	875.9269	65.8%
C Total + Soil Field Capacity	870.2329	65.4%
C Total + Soil Field Capacity + NDVI	**805.1467**	**60.5%**

Variables of soil carbon models	Average standard error	Percent error
Warm season CO_2 models		
C Total + Altitude	843.082	77.5%
C Total + Soil Field Capacity + Sunlight exposure	816.654	75.1%
-	813.556	74.8%
C Total + Slope	810.556	74.5%
Soil Field Capacity + Sunlight exposure	795.365	73.1%
C Total + Sun exposition	777.676	71.5%
C Total	776.510	71.4%
C Total + Soil Field Capacity + Slope	741.240	68.1%
C Total + Soil Field Capacity + NDVI	664.407	61.1%
Soil Field Capacity + NDVI	**602.103**	**55.3%**
Cold season CO_2 models		
Soil Field Capacity + Slope	164.891	67.9%
Soil Field Capacity + Sunlight exposure	162.912	67.1%
Soil Field Capacity	162.628	67.0%
C Total + Altitude	157.796	65.0%
-	155.795	64.1%
C Total	134.684	55.4%
C Total + NDVI	116.441	47.9%
C Total + Field Capacity + NDWI	108.983	44.9%
Soil Field Capacity + NDVI	106.277	43.8%
C Total + Field Capacity + NDWI	**89.6673**	**36.9%**
Warm season CO_2-Ctotal ratio models		
N total + NDWI	4.2166	59.9%
N Total + Sunlight exposure	4.1880	59.5%
Soil Field Capacity + N Total	4.1729	59.3%
Soil Field Capacity + Slope	4.1713	59.2%
Soil Field Capacity + N Total + slope	4.1500	58.9%
Soil Field Capacity	4.1281	58.6%
Soil Field Capacity + Sunlight exposure	4.0728	57.8%
Soil Field Capacity + N Total + Sunlight exposure	**4.0305**	**57.2%**

Variables of soil carbon models	Average standard error	Percent error
Cold season CO_2 Ctotal ratio models		
Soil Field Capacity + Altitude	1.1687	71.9%
Soil Field Capacity + N Total	1.1556	71.1%
Soil Field Capacity + N Total + Sunlight exposure	1.1530	70.9%
Soil Field Capacity + Slope	1.1510	70.8%
Soil Field Capacity	1.1398	70.1%
Soil Field Capacity + Sunlight exposure	1.1378	70.0%
Soil Field Capacity + N Total + NDWI	1.1220	69.0%
Soil Field Capacity + NDWI	**1.0920**	**67.1%**

The model was chosen according to the minimum average standard error of the calculated estimations (applying co-kriging) using soil variables and the best continuous variable, which was the one including total soil N, soil field capacity point and slope (SE= 21.5; Table 4).

The model smoothed the range of measured soil C values (68 to 556 mg C g soil^{-1}, Table 2), since the estimations ranged from 78 to 350 mg C g soil^{-1} (Figure 4). Small spots of contrasting larger and lower C ranges are found at the South of the study area, between [“y coordinate” 4042500-4050000 UTM, 18S]. The total soil C estimation plot (Figure 4) shows low spatial variability for this variable across the study area, combining mainly zones of 121-170 mg C g soil^{-1} and 171-220 mg C g soil^{-1}.

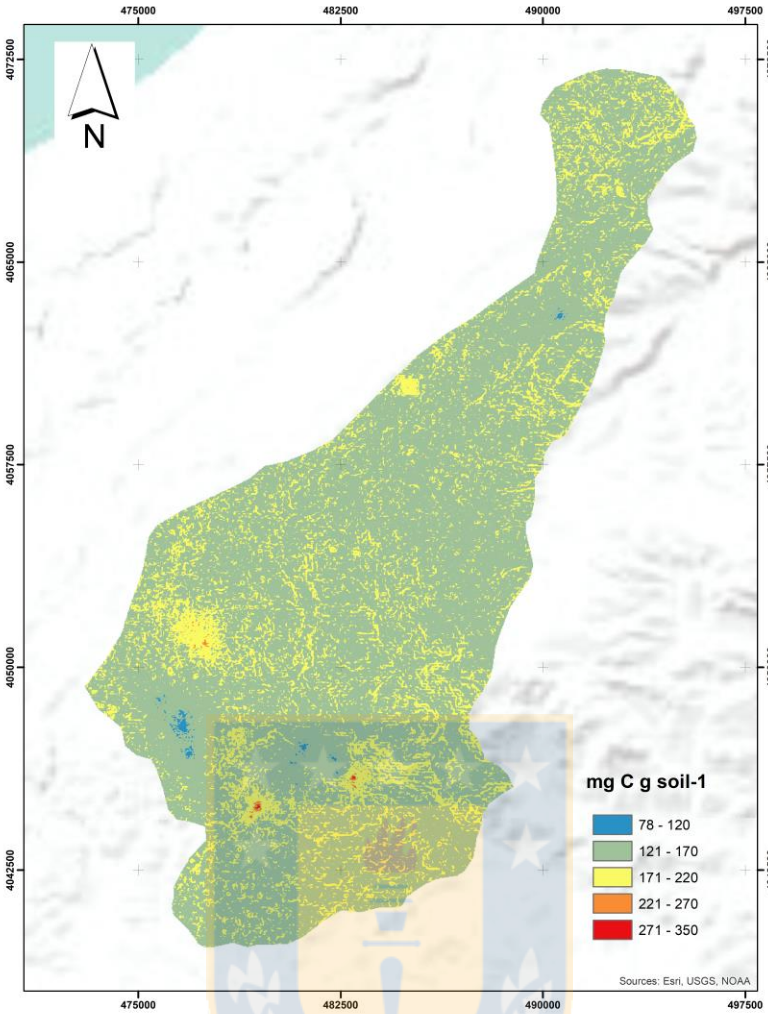

Figure 4. Spatial distribution of total soil carbon from a simulated drained peatland in Western Patagonia (Chile). Average SE=21.5. (Source: Elaborated with own data).

Modelling CO_2 emission from soil heterotrophic respiration

The relationship between the CO_2 production from heterotrophic soil respiration and discrete and continuous auxiliary variables are shown in Table 3. Besides the significant correlations observed for annual soil CO_2 emissions, a model for this variable could not be fitted because the large procedure error (Table 4). The CO_2 emissions were then modelled according to the warmer and colder season for the area following the procedure described for total soil C. The total C and N variables showed to be common influence to the CO_2 mineralized in the both seasons (Table 3), whilst soil physical variables linked to the moisture content in the soil were particularly correlated ($p < 0.01$) to the CO_2 produced in the colder season (Table 3).

The resulting CO_2 seasonal models included the total carbon and soil field capacity variable, and continuous auxiliary variables NDVI and NDWI (Table 4). It was anticipated that the warmer season showed a larger range of CO_2 emissions than the colder season (Table 2), and the outcome plots from the model estimations showed this trend (Figure 5 A-B). Information about CO_2 emissions from managed peatlands in the studied region is not available, and so threshold values are non-existing for comparison. Investigation on greenhouse gas emissions from natural peatlands in the Western Patagonia region (Chile) have been not widely produced, beyond the effort made by Broder *et al*. (2015), reporting *in situ* measurements of CO_2 for natural peatlands in Magallanes. Comparisons between those results and the data produced in this study are not appropriate, as the former results from Broder *et al.* (2015) correspond to the autotrophic and heterotrophic CO_2 emissions, measured through *in situ* techniques.

The heterotrophic CO_2 produced within the study area in the colder season registered up to 600 µg CO_2 g $soil^{-1}$ in some isolate spots, although most of the area showed values from 6 to 400 µg CO_2 g $soil^{-1}$, and 52% of the area showed values of CO2 emissions between 201-400 µg CO_2 g $soil^{-1}$ (Figure 5B). These latter values would roughly represent 2-18% of the mean CO_2 mineralized from agricultural crop rotations in the South-central Chile reported by Zagal *et al*. (2002) and Zagal and Córdova (2005). In contrast, the larger range of CO_2 values in the warmer season allowed spatial heterogeneity, and the top levels of soil CO_2 released was 4 mg CO_2 g $soil^{-1}$, but only 1% of the area reached such level (Figure 5A). Two thirds of the area showed emissions between 600-2000 µg CO_2 g $soil^{-1}$, which corresponds to 28-92% of the lowest mean CO_2 emission reported from arable crop systems, and 9-32% of the higher CO_2 levels reported by Zagal *et al*. (2002) and Zagal and Córdova (2005). However, the CO_2 levels provided by the reference studies were carried out for thirty and ten days at 22ºC, respectively, and the C mineralization rate has been assumed to be constant for a comparable period of 180 days $season^{-1}$, as measured in this study. Therefore, the modelled CO_2 values for the study region represent similar or larger emissions compared to arable soils. Despite the model error for this variable, the study area under the simulated treatment for agricultural land use seems to respond like a cropping land shortly after the drainage is in place.

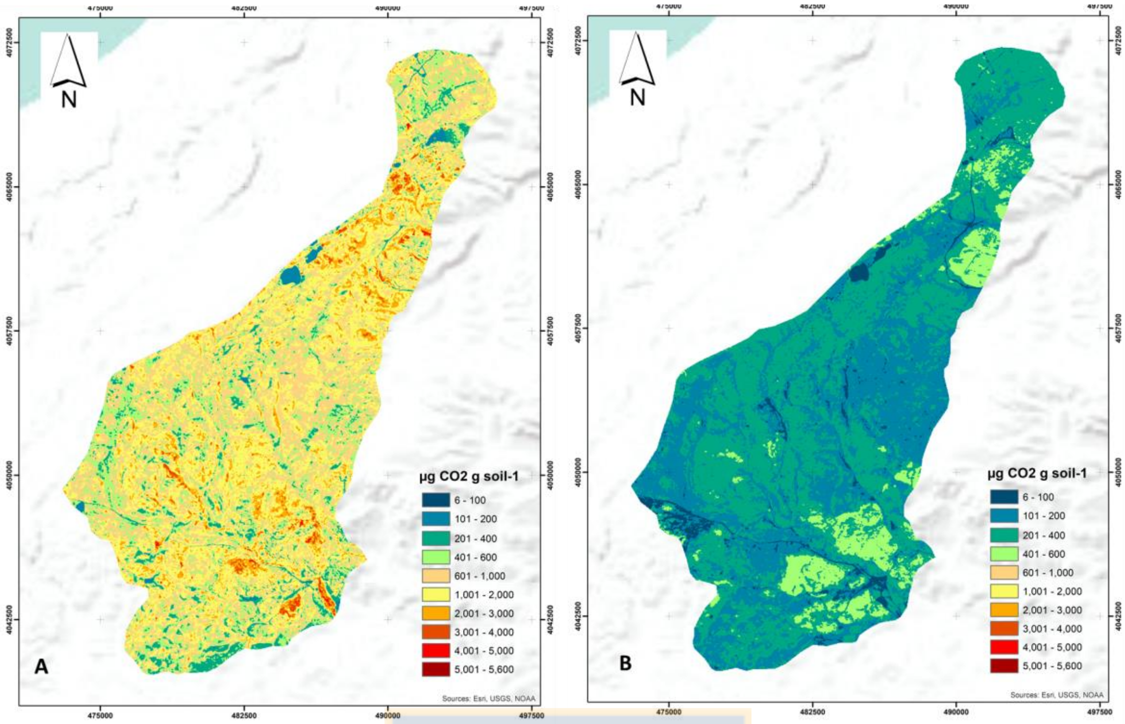

Figure 5. Spatial distribution of seasonal soil heterotrophic CO_2 emissions from a simulated drained peatland in Western Patagonia (Chile) A. Warm season soil heterotrophic CO2 emission (Average SE= 602.1) B. Cold season soil heterotrophic CO2 emission (Average SE= 89.7). (Source: Elaborated with own data).

The modelled values of CO_2 produced in the warmer season doubled the ones modelled for the colder season (Figure 5 A-B). Thus, during the warmer season the managed soil would be actively mineralizing C and producing CO_2. The colder season period in Tierra del Fuego undergoes monthly mean temperatures that maintain the microbial biomass at minimum of their biological activity (Table 2), which can be considered as the threshold of heterotrophic CO_2 emission for a managed ecosystem in the region, whilst the contrasting season would represent the effect of land use change. As the area is influenced by abiotic factors likewise cropping systems, the heterotrophic CO_2 emissions in the warmer season could register an extra increase due to the global increase of temperature. For the same reason, if the length of the warmer season in Tierra del Fuego is extended because of climate change (IPCC, 2013), the CO_2 emissions from this cold environment ecosystem might increase over the modelled values reported here.

3.3. Specific C mineralization in the study area

The ratio of mineralized CO_2 to total soil C (CO_2 Cto^{-1}) was analyzed to quantify the proportion of C metabolized by the microbial biomass shortly after a peat site is prepared for a land use change, i.e., losing the organic horizon and being drained for more suitable cropping conditions and soil moisture content. This ratio was seasonally modelled using the soil field capacity, total soil N and sunlight exposure for the warmer season and soil field capacity and NDWI for the colder season (Table 4). The spatial estimations for the CO_2 Cto^{-1} are shown in Figure 6 A-B.

A low proportion of soil C is mineralized during the colder season, also reported from Northern peatland ecosystems (Wu and Blodau, 2013). The estimated values for the study area were between 0 to 5 µg CO_2 mg C $soil^{-1}$, showing the detrimental effect of the temperature over the C mineralization, despite the soil C content. Most of the area (89%) showed a level between 0-1.5 µg CO_2 mg C $soil^{-1}$ (Figure 6B) corresponding to the larger CO_2 emission areas in the colder season (Figure 5B). In contrast, the heterotrophic mineralization of C is a larger fraction of soil C in the warmer season, when the temperatures raise, activating the microbial activity (Kirschbaum, 2013, Wang *et al*., 2016). The values of the CO_2 Cto^{-1} ratio in the warmer season (6 to 21 µg CO_2 mg C $soil^{-1}$) are above the range modelled for the colder season, but the more representative ratio for the area is 8-9 µg CO_2 mg C $soil^{-1}$, which is six times the ratio registered in the winter season.

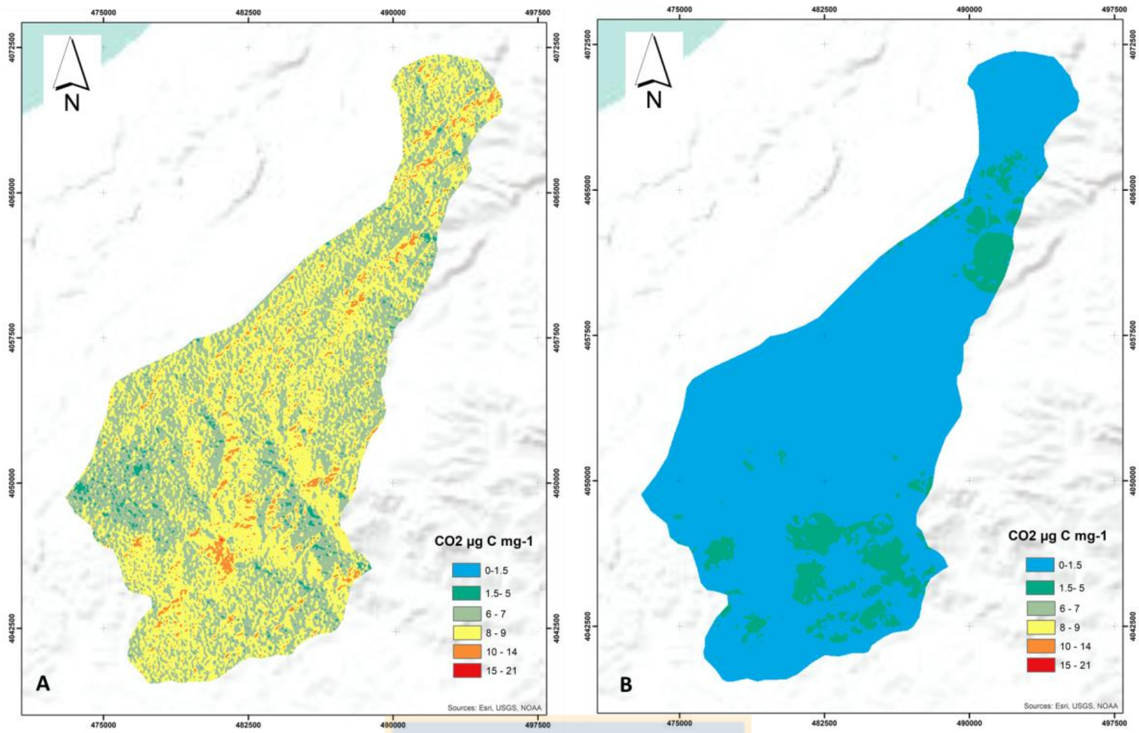

Figure 6. Spatial distribution of CO_2-Cto^{-1} ratio from a simulated drained peatland in Western Patagonia (Chile) A. Warm season CO_2-Cto^{-1} ratio (Average SE= 4.03) B. Cold season CO_2-Cto^{-1} ratio (Average SE= 1.09). (Source: Elaborated with own data)

The results imply that in the short term the terrain habilitation of peatland for cultivation in Tierra del Fuego would affect CO_2 emissions mainly in periods where the temperature $\geq$ 9°C. As consequence of climate change, temperatures will rise but also the length of warmer/colder periods as well as drought will be extended, and this might cause an increment of the C mineralization and CO_2 production. The peatlands ecosystems occupy more than 2.3 mill ha in the South of Chile (CONAF, 2011, http://sit.conaf.cl/) and there is high pressure of extraction and land use change on them. As is has being shown here, such ecosystem developed under cold conditions are responsive to temperature occurring during the warm season. Therefore, the risk of changing the use of this ecosystem would increase the C emission, and particularly in Tierra del Fuego with a long cold season where microbial biomass is less active, the new scenario of climate change is challenging regarding agricultural and environmental policies, that are requested to be operative in the short term.

Moreover, specific autotrophic or heterotrophic fluxes of C through this ecosystem have been not measured, limiting the understanding of the function of this ecosystem under natural conditions and further adaptation under anthropogenic and environmental alterations. In this study only CO_2 emissions from microbial activity were measured, which can account for 37% of the total soil respiration (Hanson *et al*., 2000). Adding the contribution of the autotrophic activity, the CO_2 emissions from a converted peatland to agricultural use, might be above the CO_2 release from an arable land. However, it appears that the C lability/resilence to the mineralization process might change as time after peatland conversion progress (Brouns *et al*., 2016). Under the conditions of this study an initial ratio of C mineralization for Western Patagonia region would be around 8-9 µg CO_2 mg C soil^{-1}; however, further studies in soil C quality (Conant *et al*., 2011) -perhaps linked to the particular natural vegetation of the ecosystem, soil microbial biomass, and microbial community identification are necessary for a better approach to the dynamics of C balance and gas emissions in this ecosystem.

CONCLUSIONS

The peat drainage condition simulated in this study through soil moisture adjustment to field capacity has shown to have temporal variability. During the warmer season in the Western Patagonia region, the C mineralization rate is larger than in the cold season due to the effect of the temperature, allowing greater range of CO2 emission values. The results from this simulation showed that once a peatland is converted to agricultural land, the CO_2 emissions can be as high as a traditional cropping system. Therefore, the land use change of this ecosystem can have a detrimental environmental cost in terms of C emissions. Chile appears within the countries with largest areas of peatland (Joosten, 2010), and Patagonia region accounts for a great proportion of those, and therefore further research is needed in order to protect this fragile ecosystem.

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CAPÍTULO 3

CONCLUSIONES GENERALES

1. La simulación de drenaje de los suelos de turbera de la región de Patagonia Occidental (Chile), resultaron en una producción casi nula de metano, por lo que la simulación de habilitación de la turbera a través del ajuste de humedad a capacidad de campo resultó satisfactoria.

2. La tasa media anual de la respiración heterotrófica del suelo en el área de estudio correspondió a 90.3 g CO_2 $m^{-2}año^{-1}$ con un máximo de 275 g CO_2 $m^{-2}año^{-1}$ y un mínimo de 18 g CO_2 $m^{-2}año^{-1}$. Por su parte, el flujo diario medio correspondió a 0.26 g CO2 $m^{-2}día^{-1}$ (de 1.13 g CO_2 $m^{-2}día^{-1}$ a 0.048 g CO_2 $m^{-2}día^{-1}$). No existen flujos anuales de CO_2 reportados en la Patagonia Chilena, sin embargo, flujos diarios han sido reportados para la respiración del ecosistema el mes de marzo que varían de 1.7 a 2.4 g CO_2 $m^{-2}día^{-1}$, siendo estos son superiores a los observados en el sitio de estudio debido a que incluyen la respiración autotrófica, y son mediciones *in situ* representativas solo de los meses cálidos.
3. La medición anual de CO_2 producto de la actividad microbiana del suelo mostró un amplio rango de valores, comparables con las emisiones de CO_2 medidos en sistemas de cultivos agrícolas. En particular se registraron valores incluso más altos que los informados para suelos cultivados. Ello posiblemente debido a la alta cantidad de C disponible para descomposición después de la aireación del suelo de turba y su exposición a mayores temperaturas.
4. Cerca del 82% de las emisiones de CO_2 anuales se generan en las estaciones de primavera y verano, que corresponden a las estaciones que presentan mayores temperaturas medias. El incremento global de temperatura aumentaría las emisiones de CO_2 en estos suelos.
5. Los modelos de estimación de C del suelo y CO_2 en diferentes estaciones del año obtuvieron valores de error altos, sin embargo permiten la estimación de mineralización a nivel de escala de sitio, en un área remota y de difícil acceso, donde no existe información acabada sobre el ciclaje de C, su balance ecosistémico, y la contribución de gases de efecto invernadero a la atmósfera.
6. Variables continuas espaciales como pendiente, exposición del sol, NDVI y

NDWI pueden ser utilizadas para mejorar mapas predictivos de CO_2-C.

7. El desarrollo de estudios que determinen los tamaños y la calidad de las fracciones de C del suelo y su tiempo de residencia en el suelo, que permitan relacionar el efecto de la extracción del horizonte orgánico de las turberas, su habilitación para uso agrícola, y manejo agrícola posterior son fundamentales. Esto permitiría decisiones informadas acerca del cambio de uso de suelo en este ecosistema de Patagonia Occidental Chilena, que se encuentra bajo una alta presión de uso antropogénico.