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## **DOCTORADO EN CIENCIAS SILVOAGROPECUARIAS Y VETERINARIAS**

### **FLUXES OF GREENHOUSE GASES IN AN ANTHROPOGENIC PEATLAND OF CHILOÉ ISLAND UNDER DIFFERENT TYPES OF USE**

FLUJOS DE GASES DE EFECTO INVERNADERO EN UNA TURBERA  
ANTROPOGÉNICA DE CHILOÉ CON DISTINTOS TIPOS DE USO

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Tesis para optar al Grado de Doctor  
en Ciencias Silvoagropecuarias y  
Veterinarias

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## **ABBREVIATIONS**

C:	Carbon
CH <sub>4</sub> :	Methane
CO <sub>2</sub> :	Carbon dioxide
GHG:	Greenhouse gases
GPP:	Gross primary productivity
GWP:	Global warming potential
N:	Nitrogen
N <sub>2</sub> O:	Nitrous dioxide
NEE:	Net ecosystem exchange
PAR:	Photosynthetically active radiation
R <sub>aut</sub> :	Autotrophic respiration
R <sub>eco</sub> :	Ecosystem respiration
R <sub>het</sub> :	Heterotrophic respiration
RH:	Relative humidity
SWF:	Soil water fraction
T <sub>air</sub> :	Air temperature
T <sub>soil</sub> :	Soil temperature
WT:	Water table

## ABSTRACT

Peatlands are wetlands of global importance because they are large reservoirs of carbon (C) and water. Permanently waterlogged soils in peatlands generate an anoxic environment, which decreases the rate of decomposition and favors accumulation of organic matter. However, changes in environmental factors can alter the decomposition process and the magnitude of fluxes of the greenhouse gases (GHG) carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O).

In Chile, peatlands are distributed from 39° to 55° S latitude, including postglacial and comparative young anthropogenic peatlands dominated by *Sphagnum magellanicum* moss. Within this range of distribution, peatlands in Chiloé Island are expected to suffer the greatest changes in temperature and precipitation due to the ongoing climate change. The previous studies on the field are concentrated on Northern Hemisphere thus there are uncertainties about ecohydrological response of southern peatlands to the climate change and their role in the GHG balance. In addition, some anthropogenic peatlands in this area are under agricultural use, being exposed to activities such *Sphagnum* moss harvesting and cattle grazing. These activities alter vegetation cover and soil compaction, but it is unknown what will be the effect of this process on GHG emissions.

The aim of this study was to estimate GHG fluxes in an anthropogenic peatland in Chiloé Island, evaluate what is their relation with environmental factors and compare GHG balance between agricultural land use, including moss harvesting and cattle grazing, and conservation land use, where only tourism and scientific activities are practiced.

We selected an anthropogenic peatland located in the north of Chiloé Island. This peatland is physically divided in two sections, one section is under strict conservation use and the other is under agricultural use. Fluxes of CO<sub>2</sub>, gross primary productivity (GPP) and ecosystem respiration (R<sub>eco</sub>), and net ecosystem exchange of CO<sub>2</sub> (NEE) were estimated using the Eddy covariance technique. Fluxes of CH<sub>4</sub> and N<sub>2</sub>O were estimated using a closed chamber system and a spectroscopic gas analyzer. Simultaneously, environmental factors were sampled. Correlation analysis and different models were constructed to evaluate the

relation of GHG fluxes with environmental factors. GHG balance was estimated as the summation of GHG annual fluxes in CO<sub>2</sub> equivalent

For the study period, the peatland section under conservation use acted as a larger sink of CO<sub>2</sub> than the agricultural managed area. The peatland under conservation use showed higher values of GPP, and the grazed and harvested area showed higher values of Reco. The main environmental drivers of GPP were temperature and photosynthetically active radiation, and the main drivers for R<sub>eco</sub> were water table depth and soil water content.

Both land use sections of the anthropogenic peatland acted as a source of CH<sub>4</sub>, however, agricultural area was three times greater source than the conservation area. Fluxes of CH<sub>4</sub> have a positive relation with total nitrogen in soil and the coverage of *Juncus procerus*, plant species that have aerenchymous tissue.

The results of this study suggest that conservation section of the peatland acted as a sink of N<sub>2</sub>O in contrast to the agricultural use area which acted as a source of N<sub>2</sub>O. Nevertheless, this difference was not statistically significant. In addition, no significant relation was found between N<sub>2</sub>O fluxes and the environmental variables measured in this study.

After de GHG balance estimation, we determined that conservation land use section of the peatland acted as a sink of GHG and the agricultural managed section acted as a source of GHG.

Land uses on anthropogenic peatland generated significant differences on their GHG fluxes and balance. Agricultural land use reduce the C sink capacity. Type of land use also generate differences on CH<sub>4</sub> and N<sub>2</sub>O fluxes. Changes on vegetation and soil conditions due to the agricultural land use could modify the GHG balance and transform the anthropogenic peatland from a sink to a source of GHG.

***Key words:*** Peatlands, environmental factors, greenhouse gases

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## 1. INTRODUCTION

Peatlands are wetlands of international importance (Ramsar 2004), because they have the capacity of regulate and store significant amounts of water (Bullock and Acreman 2003), and also, they are large carbon (C) sinks (Gorham 1991). Peatlands cover around 3% of the land surface on Earth (Aselmann and Crutzen 1989) and store between 270 to 455 Pg of C, which represents a third part of the C stored in soils (Gorham 1991).

Due to the waterlogged condition, peatland soils generate an anoxic and cold environment (Schlatter and Schlatter 2004, Van Breemen 1995) that reduce the decay rates and favor the accumulation of organic matter. Nevertheless, changes in environmental conditions can modify the process and dynamics that regulate the organic matter storage and emission of greenhouse gases (GHG) like carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). The greenhouse effect is the property to absorb and re-emit thermal radiation (long waves) increasing the temperature in the atmosphere (IPCC 1994). Between 1750 to 2011 mean temperature has increased due to the growing concentration of GHG in the atmosphere; CO<sub>2</sub> has increased from 278 to 390 ppm, CH<sub>4</sub> from 722 to 1803 ppb and N<sub>2</sub>O from 270 to 324 ppb (IPCC 2013). On the other hand, N<sub>2</sub>O is considered the main gas that has a novice impact in the Ozone layer (Ravishankara et al. 2009).

Moreover, the ecohydrological response of peatlands to the climate change is uncertain (Moore et al. 1998) which prevents predicting the future magnitude of the CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions. GHG studies on peatlands have been concentrated in the Northern Hemisphere peatlands due to their larger area (Martikainen et al. 1993, 1995, Nykänen et al. 1998, Von Arnold et al. 2005a, 2005b).

In Chile, peatlands are covered mainly by the moss *Sphagnum magellanicum* and are distributed between 39° and 55° degrees of South latitude (Díaz et al. 2012). Along this range, peatlands of Chiloé Island (between 41° and 45° degrees of South latitude) could suffer strong changes in environmental conditions due to climate change. Predictions for this zone indicate a possible reduction of precipitations between 10 and 20%, causing an increase in the water level depth, and an increase in annual temperature between 1 and 3 °C for the period 2071 to 2100 (Cabré et al. 2016). Chiloé Island landscape is a mosaic formed by temperate forests, grasslands and anthropogenic peatlands called locally as “pomponales” (Díaz and Armesto 2007). Anthropogenic peatlands have a recent origin due to wood logging or forest fires in places with poor drainage. This type of peatlands are under constant threat because are exploited to extract *Sphagnum* mosses which changes significantly the plant cover and increases the soil compaction (Díaz et al 2008). In some cases, these peatlands are used for grazing but the impact of this agricultural activity on ecosystem processes and GEI emissions is completely unknown.

Under this scenario, it is relevant to evaluate which are the effects of these activities on the magnitude of GHG fluxes in anthropogenic peatlands of Chiloé Island and estimate which is the relations of these fluxes with environmental variables.

## 2. BACKGROUND

### 2.1. Description and distribution of peatlands

Peatlands are wetlands that are characterized by the capacity to store organic matter as peat (Joosten and Clarke 2002). Peat is a vegetal substance originated by a slow decomposition process (Clymo 1983). Ecosystems that have a peat layer of 30 cm or thicker are considered as peatlands (Crum 1988). The peat layer can reach several meters of depth in peatlands of the Northern Hemisphere and in the southern cone of South America (Roig and Roig 2004). The permanent waterlogged conditions in peatlands generates and humid environment with reduced availability of oxygen and nutrients in the soil (Joosten and Clarke 2002).

Peatlands are located in low lands or in flat sites with a water level close to the soil surface (Roig and Roig 2004) where the water balance is positive, therefore, evapotranspiration is lower than precipitations (Van Breemen 1995, Mitsch and Gosselink 2000). Peatlands can be originated by two natural processes, terrestrialisation and paludification (Joosten and Clarke 2002, Roig and Roig 2004). Terrestrialisation represents the gradual colonization of a body of water by the action of the surrounding vegetation in a lagoon or after a glacier melting. Paludification is the peatland formation directly over the mineral soil after the increase in the water level.

According to their hydrology, peatlands can be classified in bogs or ombrotrophic peatlands, which only receive water and nutrients from precipitation, and fens or minerotrophic peatlands, which receive water and nutrients from precipitation and mineral soil (Limpens et al. 2008). Due to the inputs received from mineral soils, minerotrophic peatlands are richer in nutrients and less acidic than ombrotrophic peatlands (Joosten 2009). Generally, ombrotrophic peatlands have a convex surface that stands out the surrounding landscape, on the contrary, minerotrophic peatlands tend to have a concave or flat surface (Iturraspe 2010).

Peatlands cover around  $4.16 \times 10^6$  km<sup>2</sup> of the Earth surface (Joosten 2009) and 80% of these ecosystems are located in temperate cold climate zones in the Northern Hemisphere, mainly in North America, Russia and Europe. The remaining percentage of peatlands is placed in the South of Asia, Africa and South America. In Chile, peatlands are distributed from 39° degrees of south latitude and their surface cover 10,470 km<sup>2</sup> (Joosten and Clarke 2002). This area is equivalent to the 1.4% of the total surface of the country. Most of the peatlands in Chile have a glacier origin, but also there are anthropogenic peatlands called locally “pomponales”. These peatlands are originated by wood logging or forest fires in places with poor drainage (Díaz and Armesto 2007, Valenzuela-Rojas and Schalter 2004). Anthropogenic peatlands are threatened by the unregulated extraction of *Sphagnum magellanicum* moss, which is commercialized as a horticultural substrate or absorbent material (Díaz et al. 2008).

## 2.2. GHG fluxes on peatlands

Emissions of CO<sub>2</sub> in peatlands are due to autotrophic respiration (R<sub>aut</sub>) and heterotrophic respiration (R<sub>het</sub>) from the microorganism in the soil as result of the organic matter aerobic decomposition (Clymo 1984). Mean soil respiration flux in South Europe peatlands range from 80 to 541 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>, without differences between ombrotrophic and minerotrophic peatlands (Danevcic et al. 2010).

The balance of CO<sub>2</sub> fluxes allows to recognize if an ecosystem is acting as a source or a sink. CO<sub>2</sub> balance or net ecosystem exchange (NEE) is equivalent to the difference between gross primary productivity (GPP), that represent the CO<sub>2</sub> captured by photosynthesis process, and ecosystem respiration (R<sub>eco</sub>), CO<sub>2</sub> emitted by R<sub>aut</sub> and R<sub>het</sub> (Bubbier et al. 2003).

Because GPP is by convention represented by negative values and R<sub>eco</sub> by positive values, negative values of NEE indicate that the ecosystem is a sink of CO<sub>2</sub> and positive values indicate that is a source of CO<sub>2</sub>. A previous study in a Finnish peatland found that most part of the year the ecosystem acted as a sink of CO<sub>2</sub>; the diurnal fluxes varied from -0.12 to -0.04 mg CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> between summer and autumn, and the night fluxes varied from 0.07 to 0.04 mg CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> (Aurela et al. 1998). This behavior is similar to that found by Schulze et al. (2002) in Siberia, where an ombrotrophic peatland dominated by *Sphagnum* mosses acted as a significant sink of CO<sub>2</sub>. Another study in an ombrotrophic peatland in Canada, showed that annual NEE was -248 ± 68 g CO<sub>2</sub> m<sup>-2</sup> year<sup>-1</sup> (Laffleur et al. 2001). Nevertheless, Shurpali et al. (1995) found interannual variability in a peatland of Minnesota (USA), where from one year to the next the ecosystem turned from a sink to a source of CO<sub>2</sub> due to the peatland sensitivity to environmental changes.

Production of CH<sub>4</sub> or methanogenesis occurs due to the anaerobic decomposition in logged soil conditions (Clymo 1984, Zinder 1993). Methane produced in the deeper layers of the soil can be released to the atmosphere by diffusion, ebullition and passive transport in plants with aerenchymous tissue (Chanton 2005). Annual flux of CH<sub>4</sub> in European peatlands range from -0.28 to 50.93 g CH<sub>4</sub> m<sup>-2</sup> year<sup>-1</sup> (Danevcic et al. 2010).

Production of N<sub>2</sub>O occurs due to microbial nitrification and denitrification of the organic nitrogen in soil (Davidson 1991). Nitrification, is an aerobic process that can reach up to 80% of the N<sub>2</sub>O emission from peatland soils (Webster and Hopkins, 1996; Pihlatie et al. 2004). Unlike nitrification, denitrification is an anaerobic process that is controlled mainly by the availability of nitrates (Conrad, 1996; Davidson et al. 2000; Öquist et al. 2007). Annual flux of N<sub>2</sub>O in European peatlands ranges from 0.004 to 9.52 g N<sub>2</sub>O m<sup>-2</sup> year<sup>-1</sup> (Danevcic et al. 2010). Emissions of N<sub>2</sub>O from undisturbed peatland of Europe are lower than other terrestrial ecosystems (Martikainen et al. 1993).

### 2.3. Environmental factors that control GHG fluxes on peatlands

Water table level is one of the main environmental factors that regulate GHG emissions in peatlands due to the caloric capacity of water that generates a thermal buffer (Hooijer et al. 2010) and the lower diffusion of gases in this matrix that limits the availability of oxygen (Joosten and Clarke 2002). When the water table deepens, the incorporation of oxygen to the soil increases, stimulating the aerobic decomposition of the organic matter and, in consequence, favoring the heterotrophic production of CO<sub>2</sub> (Hooijer et al. 2010). However, it is not clear which is the effect on the R<sub>aut</sub> so it is difficult to estimate the effect on R<sub>eco</sub>.

On the other hand, when water table level is closer to the soil surface, CH<sub>4</sub> is the main GHG emitted to the atmosphere. Several studies have found a negative relationship between water table depth and emission of CH<sub>4</sub> in peatlands (Roulet et al. 1992, Huttunen et al. 2003, Laiho 2006, Ojanen et al. 2010, Danevcic et al. 2010).

Water table level also has an effect on the emission of N<sub>2</sub>O because it modifies the nitrification and denitrification rates, however, previous studies have shown different results depending on the type of soil (Melling et al. 2007). Some studies have detected higher emissions of N<sub>2</sub>O in intermediate levels of the water table, where aerobic and anaerobic production of N<sub>2</sub>O are in equilibrium (Martikainen et al. 1993). Other studies have found higher emissions of N<sub>2</sub>O under lower water table levels, where nitrification activity increases considerably (Zimenko and Misnik, 1969; Williams and Wheatly 1988, Regina et al. 1996).

Nykänen (2003) pointed out that these results cannot be generalized because they depend on the availability of nutrient and the type of peatland. Minerotrophic peatlands have greater availability of nitrates and could experience an increase the N<sub>2</sub>O emissions under low water levels (Martikainen et al. 1995, Laine et al. 1996, Nykänen 2003). On the contrary, ombrotrophic peatlands that have lower availability of nutrients, have not shown changes in N<sub>2</sub>O emissions after a decrease in water table depth (Laine et al. 1996, Nykänen 2003, Von Arnold et al. 2005a, 2005b).

Temperature is another environmental factor that has a relevant effect on GHG emissions in peatlands. Previous studies have found a positive relation between temperature and CO<sub>2</sub> emissions (Silvola et al. 1996, Dorrepaal et al. 2009, Ojanen et al. 2010, Danevcic et al. 2010), which could be even higher under high humidity conditions (Silvola et al. 1996, Mäkiranta et al. 2009). Temperature also has a positive effect on CH<sub>4</sub> production (Roulet et al. 1992, Schulz and Conrad 1996, Avery et al. 1999, Hines et al. 2001; Duddleston et al. 2002, Huttunen et al. 2003, Smith et al. 2010). However, a previous study in European peatlands did not find relation between N<sub>2</sub>O emissions and soil temperature (Danevcic et al. 2010).

Cover of vascular plants could have a significant effect on GHG emissions. Some vascular plants have aerenchymous tissue which mobilizes gases from the roots to the atmosphere and vice versa. Through this tissue, plants can incorporate oxygen to the

anoxic soil layers, which favors CO<sub>2</sub> production (Striker et al. 2007, De Deyn et al. 2008). Besides, these plants can mobilize CH<sub>4</sub> from deeper layers of the soil to the atmosphere (Nilsson et al. 2001, Whiting and Chanton 1993, Joabsson et al. 1999). The group of aerenchymous plants is formed by species of the genera *Nymphaeae*, *Nuphar*, *Calla*, *Peltandra*, *Sagittaria*, *Cladium*, *Glyceria*, *Scirpus*, *Eleocharis*, *Eriophorum*, *Scheuchzeria*, *Phragmites*, *Typha*, *Juncus* and *Carex*, among others (Couwenberg 2009).

Several studies have reported a positive relationship between vascular plant cover and CH<sub>4</sub> emissions in peatlands (Schimel 1995; Ojanen et al. 2010). Greenup et al. (2000) indicate that CH<sub>4</sub> emission in a peatland could be six times greater in places with vascular plants. Another study in United Kingdom, showed that CO<sub>2</sub> as CH<sub>4</sub> emissions were greater in peatlands dominated by *Eriophorum spp.* than other sites dominated by *Sphagnum* mosses (MacNamara et al. 2008).

Another relevant environmental factor is the availability of nitrogen in soils but its effect on GHG emissions has been less studied. Generally, CO<sub>2</sub> emissions are higher in fertile soils than in nutrient poor soils (Von Arnold et al., 2005a; Minkkinen et al., 2007; Silvola et al., 1996; Couwenberg et al. 2011). However, there is scarce knowledge about the relation of nitrogen soil content and the magnitude of CO<sub>2</sub> and CH<sub>4</sub> emissions in peatlands. A field experiment in an oligotrophic peatland did not find differences in CO<sub>2</sub> and CH<sub>4</sub> emissions two years after 3 g of NH<sub>4</sub>NO<sub>3</sub>-N m<sup>-2</sup> year<sup>-1</sup> were artificially added (Saarnio 2003). Another six-year experiment in an ombrotrophic peatland dominated by *Sphagnum* mosses did not find differences in CH<sub>4</sub> emissions after adding 10 g of NH<sub>4</sub>NO<sub>3</sub>-N m<sup>-2</sup> year<sup>-1</sup> (Nykänen et al. 2003). On the contrary, in drained peatlands of Sweden, emissions of N<sub>2</sub>O showed an exponential decrease when the C:N ratio in soil increase (Klemetsson et al. 2005). This coincides with Ojanen et al. (2010), who reported a negative strong relationship between N<sub>2</sub>O emission and C:N ratio.

#### 2.4. Anthropogenic peatlands of Chiloé Island

Chiloé Island is located between 41° and 44° degrees of South latitude. During the Quaternary glacial period, a significant part of this island was covered by ice (Villagrán 1990). This fact added to the poor drainage in soils generates optimal conditions for the development of peatlands (Hauser 1996). Peatland formation occurs due to the plant colonization of the water body after glaciers melting (Villagrán 1991). Nevertheless, this is not the only process that has generated peatlands in the island. Since the middle of 19th century, the strong pressure over the territory due to the land use change favored wood logging and forest fires to remove the forest coverage which generated anthropogenic peatlands (Díaz et al. 2008; Zegers et al. 2006).

Anthropogenic peatlands are different to glacial peatlands in multiple aspects. Due to their recent origin, anthropogenic peatlands have lower amounts of peat than glacial peatlands. Their plant composition is richer than glacial peatlands, as a result of a process that mixed species adapted to high humidity conditions and plant species that became

from the surrounding forest, pastures and croplands (Díaz et al 2008). Glacial peatlands richness of vascular plants is generally below 15 species and are dominated by *Juncus spp.*, *Sphagnum spp.* and Cyperaceae species (Hauser 1996). Despite these differences, both types of peatlands have aerenchymous species such as *Carex magellanica* and *Juncus procerus*.

In hydrological terms, glacial peatlands are ombrotrophic, rising up over the soil surface. In contrast, anthropogenic peatlands are minerotrophic, located in lower lands and receiving water and nutrients from soil and precipitation. However, it is common to find outstanding patches dominated by *Sphagnum magellanicum* that could be an early stage in the ecological succession to an ombrotrophic peatland. Also, it is important to indicate that anthropogenic peatlands usually have a water table level close to the soil surface, which generates water logged terrains along the year (Díaz et al. 2008).

Chiloé peatlands are exploited for peat and also for *Sphagnum* mosses extraction. During the period 2003-2012, Chile have exported a mean of 2,675 tons of *Sphagnum* mosses per year, being the main destination markets Taiwan, USA, Japan, South Korea, Netherlands, China, Vietnam and France, where the mosses are used as horticultural substrate (ODEPA 2012). The growing demand and the absence of regulation have caused that some farmers extract this resource indiscriminately, generating the degradation of these wetlands (Díaz et al. 2008).

This situation, added to other local activities as grazing, could generate a great impact in anthropogenic peatlands because they are transition ecosystems, therefore, changes in their vegetation or in the environmental variables are expected to regulate their dynamics and modify the GHG balance.

### **3. HYPOTHESIS**

#### 3.1. General hypothesis

Land use could modify the balance of GHG fluxes in an anthropogenic peatland due to the changes in vegetation and soil.

#### 3.2. Specific hypothesis

Due to their recent origin, anthropogenic peatlands could act as a sink of CO<sub>2</sub>. Water table level could be the environmental variable that better explains the magnitude of CO<sub>2</sub> fluxes.

Agricultural use of an anthropogenic peatland could modify the GHG balance due to the changes in vegetation, water table level and soil conditions.

The type of plant cover of an anthropogenic peatland could explain the magnitude of GHG fluxes due to the mobilization of gases from deeper soil layers.

### **4. OBJECTIVES**

#### 4.1. General objective

To compare the GHG balance in an anthropogenic peatland under conservation and agricultural land uses.

#### 4.2. Specific objectives

To compare the CO<sub>2</sub> balance in an anthropogenic peatland under conservation and agricultural land uses and evaluate its relation with micrometeorological variables.

To compare the CH<sub>4</sub> and N<sub>2</sub>O balances in an anthropogenic peatland under conservation and agricultural land uses and evaluate its relation with micrometeorological and vegetation variables.

To analyze the effect of land use on the GHG balance in an anthropogenic peatland.

# EFFECTS OF AGRICULTURAL LAND USE ON THE CARBON DIOXIDE BALANCE OF AN ANTHROPOGENIC PEATLAND IN NORTHERN PATAGONIA

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## ABSTRACT

Peatlands are characterized by their large carbon (C) storage capacity and may represent important C sinks globally. In southern Chile, young peatlands (few centuries old) have originated by logging or fires in forest sites with high precipitation and poorly drained soils. These novel ecosystems are called anthropogenic peatlands and their role in the regional C cycle is unknown. Here we present 18-months measurements of net ecosystem exchange (NEE) of carbon dioxide (CO<sub>2</sub>) in an anthropogenic peatland in northern Chiloé Island, this peatland is partly used for conservation and partly used for agriculture (cattle grazing and *Sphagnum* moss extraction). Gross primary productivity (GPP) and ecosystem respiration (R<sub>eco</sub>) were estimated from NEE for the same study period. Statistical models were used to identify micrometeorological variables that explain the magnitude of these CO<sub>2</sub> fluxes. For the study period, the conservation area of the peatland acted as a larger C sink (-759.9 g CO<sub>2</sub> m<sup>-2</sup> year<sup>-1</sup>) than the agricultural area (-258.1 g CO<sub>2</sub> m<sup>-2</sup> year<sup>-1</sup>). The peatland under conservation use showed higher values of GPP, whereas the grazed and harvested area showed higher values of R<sub>eco</sub>. While GPP had positive significant correlation with air temperature and photosynthetically active radiation, R<sub>eco</sub> had positive correlation with air and soil temperature, and negative correlation with water table depth and soil water fraction. Land use type in this anthropogenic peatland generates marked differences in the C balance, i.e., agricultural use reduces its C sink capacity.

Keywords: *Sphagnum magellanicum*, carbon balance, Southern Hemisphere, moss harvest, minerotrophic peatland.



## 1. Introduction

Peatlands are wetlands of global and regional importance (Ramsar 2013), because of their capacity to regulate and store significant volumes of water (Bullock and Acreman 2003) and at the same time acting as significant sinks and storages of carbon (C) (Gorham 1991, Yu 2012). Peatlands are naturally formed in places where the water balance is positive, i.e., evapotranspiration is lower than precipitation (Van Breemen 1995). According to their hydrology, peatlands are classified as bogs or ombrotrophic peatlands, which only receive water and nutrients from precipitation, and fens or minerotrophic peatlands, which receive water and nutrients from precipitation and minerogenic waters (Limpens et al. 2008). Although peatlands cover only 2.8% of the terrestrial surface of the Earth (Xu et al. 2018), they store 270–370 Tg C (Turunen et al. 2002), equivalent to 32 – 44% of the current CO<sub>2</sub> in the atmosphere (IPCC 2013).

Due to their waterlogged condition, peatland soils are anoxic and cold environments (Schlatter and Schlatter 2004; Van Breemen 1995). These conditions reduce the heterotrophic decomposition rate, which favors organic matter accumulation (Clymo 1984). However, changes in environmental conditions can modify biogeochemical processes and the dynamics that regulate organic matter accumulation, altering the magnitude of CO<sub>2</sub> emissions (Post 1990).

The net ecosystem exchange (NEE) reflects the balance of CO<sub>2</sub> fluxes between the ecosystem and the atmosphere, and it is used to estimate the ecosystem carbon balance (Chapin et al. 2006); positive values of NEE indicate release of CO<sub>2</sub> and negative values indicate that the ecosystem is acting as a sink of CO<sub>2</sub>. Generally, peatlands act as a sink of CO<sub>2</sub>, with most studies reporting a mean annual NEE range from -73 to -220 g CO<sub>2</sub> m<sup>-2</sup> year<sup>-1</sup>, and a similar temporal variability between minerotrophic and ombrotrophic peatlands (Limpens et al. 2008).

Precipitation and temperature are recognized as essential factors in the eco-hydrological response of peatlands to the climate change, but nevertheless, there are uncertainties due to the scarce quantification of the feedbacks across different types of peatlands and time scales (Waddington et al. 2015), which makes difficult to predict the magnitude of CO<sub>2</sub> emissions in the future.

In Chile, peatlands are distributed from 39° to 55° S, including postglacial and comparatively young anthropogenic peatlands, which are dominated mainly by *Sphagnum magellanicum* (Díaz et al. 2012). Some recent anthropogenic peatlands have originated after logging or fire in forest sites where precipitation is over 2,000 mm and soils are poorly drained or seasonally flooded (Díaz et al. 2008; Zegers et al. 2006). In this latitudinal range, North-Patagonian peatlands in Chiloé Island (from 41° to 45° S), could experience high alterations due to ongoing climate change. Climate simulations for South America region predict that Patagonia could suffer from 10 to 20% decrease in precipitation, which regulates water table level and soil moisture, and also an increase in mean temperature from 1 to 3 °C, for the 2071-2100 period (Cabré et al. 2016). Moreover, some peatlands in this area are under agricultural land use, represented by the extraction of *Sphagnum* moss that is used as a

horticultural substrate (Díaz et al. 2008), and by small-scale cattle grazing. The effects of these activities on CO<sub>2</sub> fluxes and balance in anthropogenic peatlands have not been studied.

We measured CO<sub>2</sub> fluxes during 18 months in an anthropogenic peatland in Chiloé Island that is under conservation and agricultural land uses, using the eddy covariance technique. The objectives of the study were: 1) to estimate the seasonal variability of C fluxes, 2) to identify the main environmental drivers that regulate these C fluxes, and 3) to estimate the effect of different types of land use on the C balance.

## 2. Methods

### 2.1. Study area

The study area is located in the north-east of Chiloé Island (41°52'S 73°40'E), Los Lagos Region, Chile (Fig. 1 A). The landscape is dominated by a mosaic of Valdivian and North-Patagonian temperate evergreen forests (Veblen et al. 1997), grazing pastures, secondary shrublands and small croplands (Aravena et al. 2002). In the north of Chiloé Island, temperate forests were affected by extensive fires and logging; those human activities generated patches of shrublands and anthropogenic peatlands covered by *Sphagnum* mosses (Díaz et al. 2008). The climate is temperate with a strong oceanic influence (Di Castri and Hajek 1976). Precipitation ranges from 2,000 to 2,500 mm; the minimum monthly temperature is 3 °C (July), and the maximum temperature is 17 °C (January) (Carmona et al. 2010). Soils have been classified as “ñadis” type, Duric Histic Placaquand according to the US soil taxonomy (USDA 2014), derived from Holocene volcanic ashes over glaciofluvial deposits with a high presence of organic matter and characterized by having an impermeable layer at 50-60 cm depth (Hedin et al. 1995; Dec et al. 2017; Veit and Garleff 1996). This impermeable layer generates waterlogged soil conditions during the winter (June to August), particularly when forest cover is absent (Díaz et al. 2007). The peatland selected for study is a minerotrophic peatland, covering approximately 16 ha, that has two types of land use (Fig. 1B). One section of the peatland, which belongs to Senda Darwin Biological Station (SDBS), is used for conservation (5.5 ha), without major intervention during the last 20 years, except for tourist visits and scientific activities. In contrast, the other section of the peatland is part of a private farm currently practicing agricultural use (10.5 ha), including moss extraction and cattle grazing. The *Sphagnum* moss is being extracted for commercial purposes (approximately 10 kg of dry moss ha<sup>-1</sup> month<sup>-1</sup> are being sold to third parties) (Cabezas et al. 2015), while cattle grazing causes physical disturbance of the moss layer, soil compaction, and a decrease of woody vegetation.

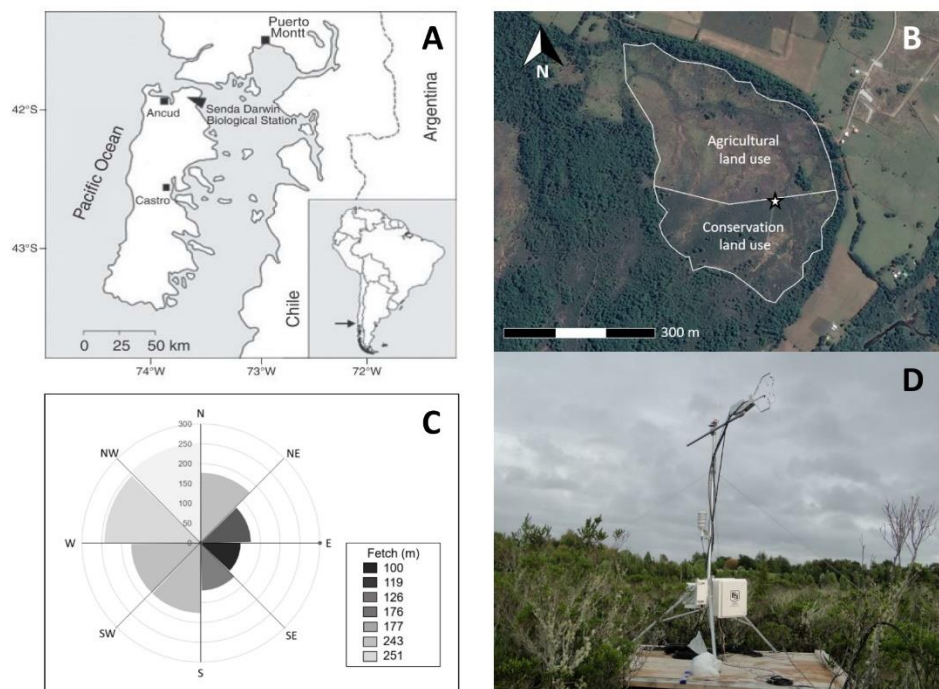


Figure 1. A) Study area located at Senda Darwin Biological Station, Chiloé Island, Chile; B) Location of the different types of land use in the anthropogenic peatland (star indicates location of eddy covariance station); C) Fetch of fluxes measured in the anthropogenic peatland, according to the wind direction; D) View of the eddy covariance station, installed 3 m above the soil surface.

The vegetation of the area has a heterogeneous composition, where the most frequent woody species are the low shrubs *Myrteola nummularia* and *Gaultheria mucronata*, interspersed with thick patches of *Sphagnum* mosses (Cabezas et al. 2015). There are patches of aquatic plants (e.g., *Juncus sp.* and *Apodasmia chilense*), ferns (e.g., *Blechnum magellanicum*), scattered tree saplings (e.g., *Eucryphia cordifolia* and *Tepualia stipularis*), and herbs from crops and pastures (e.g., *Aster vahlii*, *Centella asiatica*) (Díaz et al. 2008). According to Cabezas et al. (2015), there are significant differences in plant composition and structure between types of land use in this anthropogenic peatland. Conservation area has a clear dominance of *Sticherus cryptocarpus* and *Baccharis patagonica*, while the agricultural area has high coverage of herbaceous species without a clear dominant species, similar to a pasture. The agricultural area has higher richness of plant species, but with a higher percentage of exotic species. The mean peat depth is 0.29 m and the mean C content is  $11.99 \pm 0.77 \text{ kg C m}^{-2}$ , showing a significantly higher amount of C aboveground in the conservation management area, but no differences in belowground C content (Cabezas et al. 2015).

## 2.2. Eddy covariance measurements

Net ecosystem exchange was estimated using the eddy covariance methodology (Hicks 1970; Kaimal 1973; Wesely and Hicks 1977; Baldocchi 2003). The eddy covariance station (model CPEC200, Campbell Scientific Inc., Logan, USA) is composed of a sonic anemometer (model CSAT-3), an infrared gases analyzer (model EC155), an air pump and a datalogger (model CR3000) (Burba 2013). The sonic anemometer measures wind velocity in three dimensions. The infrared gas analyzer measures atmospheric CO<sub>2</sub> concentration. Both instruments were installed 3 m above the soil surface (Fig. 1D). Measurements were done during 18 months (April 2015 - October 2016) with a frequency of 10 Hz, and fluxes were calculated as the covariance of vertical wind speed and CO<sub>2</sub> concentration for 30-minute periods as:

$$F = \overline{w'c'}, \quad (\text{Equation 1})$$

where  $w'$  is mean vertical velocity deviation of the wind (m s<sup>-1</sup>) and  $c'$  is mass CO<sub>2</sub> concentration deviation (μg m<sup>-3</sup>) (Aubinet et al. 2000; Hargreaves et al. 2001). Effects of fluctuations on air density were managed by converting mole fractions to mass concentration (Humphreys et al. 2006).

Calculations of NEE were performed using the EddyPro software (LICOR, 4.1.0 version). Quality control and corrections of the CO<sub>2</sub> flux were applied due to issues with the functioning of the eddy covariance station and during periods with adverse meteorological conditions. Data from periods with insufficient power supply, anomalous peaks in the CO<sub>2</sub> concentration and insufficient turbulence (air friction velocity < 0.1 m s<sup>-1</sup>) were discarded (Gu et al. 2005). According to Korman and Meixener (2001), we also discarded data when the flux footprint exceeded the fetch, which varied according to the wind direction (Fig. 1C).

For the study period, 9,481 valid half-hour data fluxes were obtained (6,915 from the agricultural use section and 2,566 from the section under conservation use), which represent 35% of the original data set (see more details in the Appendices). The time series were gap-filled using the Look-Up Table method (Reichstein et al. 2005). To separate fluxes from the sections of the peatland subjected to different land use, values of wind direction and footprint of the flux were used. After separating the data into two datasets (one for each section of the peatland), a second gap-filling was performed on each dataset.

The partitioning of NEE allowed estimating ecosystem respiration ( $R_{\text{eco}}$ ) and gross primary productivity (GPP). With these values, a regression between  $R_{\text{eco}}$  and air temperature was built according to Lloyd and Taylor (1994). This regression allowed us to estimate  $R_{\text{eco}}$  during daytime. The gap-filling and the flux partition were performed using the REddyProc R package developed by the Max-Planck Institute for Biogeochemistry ([www.bgc-jena.mpg.de/~MDIwork/eddyproc/](http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/)). To estimate the annual CO<sub>2</sub> balance, data from the first year of measurements were considered.

### 2.3. Micrometeorological variables

In parallel to the flux measurements, micrometeorological variables were recorded for the same study period. Air temperature ( $T_{air}$ ) and relative humidity (RH) were measured using a combined sensor (model HMP155, Vaisala, Helsinki, Finland) at 3 m above the ground. Soil temperature ( $T_{soil}$ ) and soil water fraction (SWF) were measured with three sets of thermocouples (model TCAV, Campbell Scientific) and water content reflectometers (model CS616, Campbell Scientific), installed at 5 cm depth in three points with different types of plant coverage (shrubs, herbs and moss). Water table level (WT) was measured using two submersible pressure transducers (model CS451, Campbell Scientific). Measurements of photosynthetically active radiation (PAR) were made using a quantum sensor (model LI190SB, LI-COR, Lincoln, Nebraska) placed at 3 m above the ground. Mean values for 30-minute records for each variable were stored in the datalogger.

### 2.4. Data analysis

Statistical models were fit for mean half hour  $CO_2$  fluxes and micrometeorological variables. A hyperbolic curve was fit to describe the light response of GPP to PAR:

$$GPP = \alpha * PAR / (\beta + PAR), \quad (\text{Equation 2})$$

where  $\alpha$  indicates the maximum GPP ( $g\ CO_2\ m^{-2}\ s^{-1}$ ) and  $\beta$  represents PAR at half maximum GPP ( $\mu\text{mol photons}\ m^{-2}\ s^{-1}$ ). Relation of  $R_{eco}$  and temperature was fit to an exponential curve (Equation 3). Relation of  $R_{eco}$  and WT was fit to a quadratic polynomial curve (Equation 4), and the relation of  $R_{eco}$  and SWF was fit to a negative exponential curve (Equation 5).

$$R_{eco} = a * \exp^{(b * T)} \quad (\text{Equation 3})$$

$$R_{eco} = a * WT + b * WT^2 + n \quad (\text{Equation 4})$$

$$R_{eco} = a * \exp^{(-b * SWF)} \quad (\text{Equation 5})$$

Coefficient of determination ( $R^2$ ) was estimated for each model to analyze the percentage of variability of  $CO_2$  fluxes explained by each micrometeorological variable. Statistical analyses were performed using R-project software (version 3.0.1).

### 3. Results

#### 3.1. Micrometeorological conditions

During the study period, the daytime mean cumulative PAR was  $12,027 \pm 0.18 \mu\text{mol photons m}^{-2} \text{ day}^{-1}$  (Fig. 2A). In autumn and winter values of PAR remained below  $10,000 \mu\text{mol photons m}^{-2} \text{ day}^{-1}$ , and increased rapidly during the spring and summer reaching  $35,000 \mu\text{mol photons m}^{-2} \text{ day}^{-1}$ . The daily average RH ranged from 14.9 to 100 % (Fig. 2B), while air and soil temperature ranged from 1.1 to  $18.0 \text{ }^\circ\text{C}$  and 4.2 to  $16.6 \text{ }^\circ\text{C}$ , respectively (Fig. 2C). The values of SWF and WT varied widely (from 10.3 to 82.4%, and from  $-72.3$  to  $0 \text{ cm}$ , respectively), reaching their minimum values in late summer (Fig. 2D).

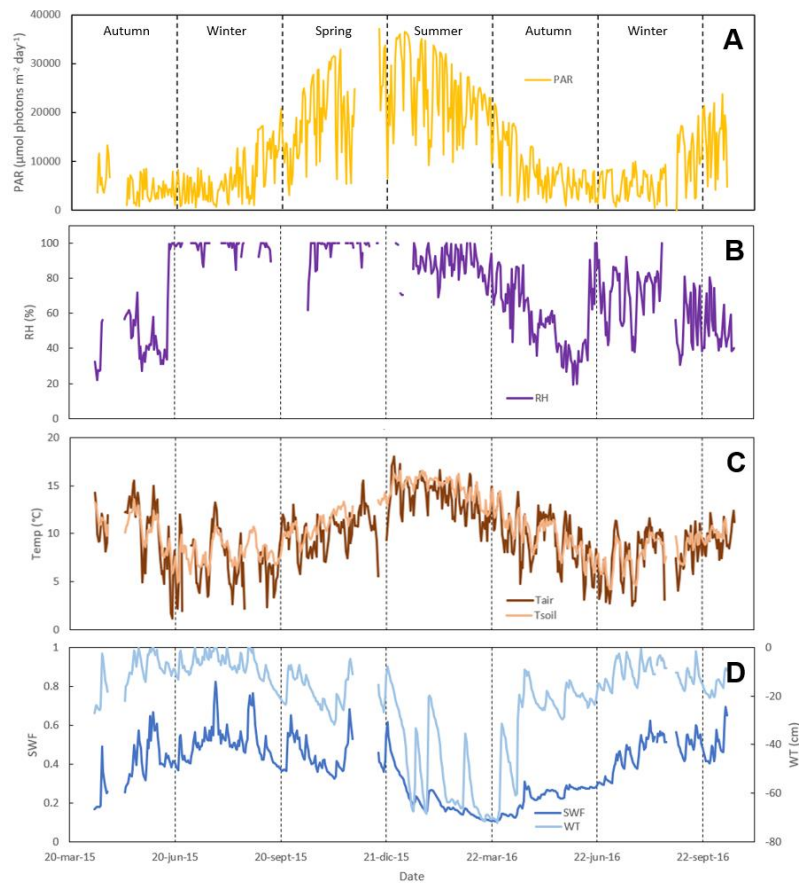


Figure 2. Environmental conditions in the anthropogenic peatland. Daily mean values of A) cumulative daily photosynthetically active radiation (PAR), B) air relative humidity (RH), C) air temperature ( $T_{\text{air}}$ ), soil temperature ( $T_{\text{soil}}$ ), D) soil water fraction (SWF) and water table depth (WT).

### 3.2. Carbon dioxide fluxes

During autumn and winter (March to September), the daily fluxes of GPP and  $R_{\text{eco}}$  were small and showed low variability (Figure 3). Frequently during these cold and humid seasons,  $R_{\text{eco}}$  was higher than GPP, generating positive values of NEE (source of  $\text{CO}_2$ ). This behavior can be attributed to lower temperature and limited solar radiation values (Figure 2). However, the magnitude of the  $\text{CO}_2$  fluxes increased significantly during the spring and summer (from late October to early March) in both types of land uses of the peatland (Figure 3). During these seasons, NEE was often negative (sink of  $\text{CO}_2$ ) and significantly higher in magnitude than the rest of the year. The highest fluxes of  $R_{\text{eco}}$  were observed in February (summer) and the lowest in September. The highest fluxes of GPP were reached in February (summer) and the lowest in June (winter). Along the study period, the peatland area used for agriculture showed the highest values of  $R_{\text{eco}}$  (Table 1). The values of NEE showed that both land use types are sinks of  $\text{CO}_2$ , but in the conservation side of the peatland NEE was larger than the agricultural side (Table 1). The section under conservation land use showed a cumulative annual NEE of  $-759.9 \text{ g CO}_2 \text{ m}^{-2} \text{ year}^{-1}$ , which means that it is a higher sink than the agricultural use side, where annual NEE was  $-258.1 \text{ g CO}_2 \text{ m}^{-2} \text{ year}^{-1}$  (66% lower).

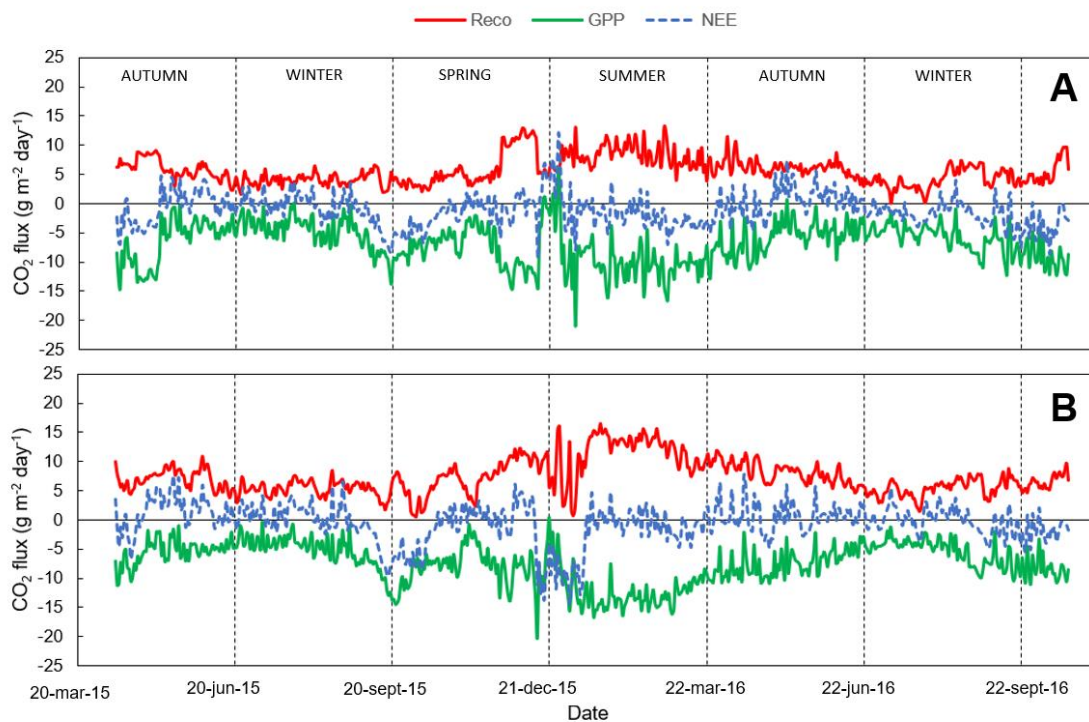


Figure 3. Carbon dioxide fluxes in an anthropogenic peatland used for A) conservation and B) agriculture. Vertical dashed lines separated seasons.

Table 1 Fluxes of CO<sub>2</sub> (g CO<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup>) in an anthropogenic peatland with conservation and agricultural land use.

Flux	Land use	Mean	SE	Min	Max
NEE	Agricultural	-0.71	0.005	-14.37	7.65
	Conservation	-2.08	0.005	-12.02	4.76
R <sub>ecco</sub>	Agricultural	7.92	0.005	0.46	16.52
	Conservation	4.82	0.005	0.21	12.31
GPP	Agricultural	-7.87	0.005	-20.23	-0.31
	Conservation	-6.88	0.005	-20.03	-0.04

### 3.3. Drivers of CO<sub>2</sub> fluxes

The GPP flux only showed a significant positive relation with PAR and air temperature. Under the same PAR conditions, the conservation use area of the peatland reached higher values of GPP (Fig. 4). Values of GPP for the conservation area tended to stabilize around 9.6 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> from PAR values of 1000 μmol photons m<sup>-2</sup> s<sup>-1</sup>, while it stabilized around 8.3 μmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup> from PAR values of 800 μmol photons m<sup>-2</sup> s<sup>-1</sup> at the agricultural area. Comparing seasons, autumn and summer showed significantly higher maximum GPP than winter and spring (Fig. 5). For both types of management, autumn season values of GPP showed the best fit to the logistic curve, being also the only period when maximum GPP (β) was higher in the agricultural use compared to the conservation use (Table 2).

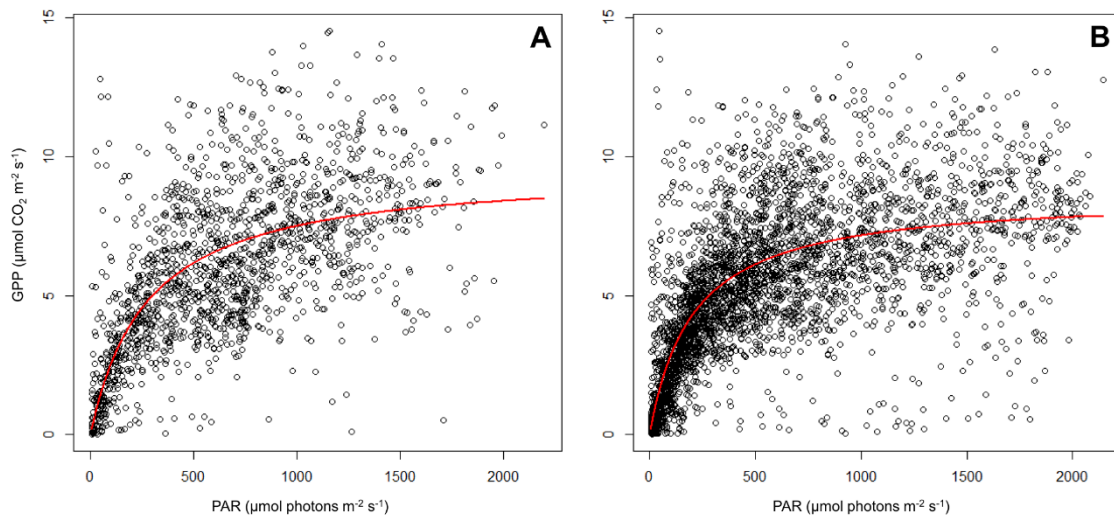


Figure. 4. Relation of GPP and PAR in an anthropogenic peatland. A) Conservation land use section ( $GPP = 9.569 * PAR / (274.190 + PAR)$ ;  $R^2=0.42$ ;  $p<0.05$ ), B) Agricultural land use section ( $GPP = 8.343 * PAR / (203.626 + PAR)$ ;  $R^2=0.51$ ;  $p<0.05$ ). Points represent 30-minute periods.



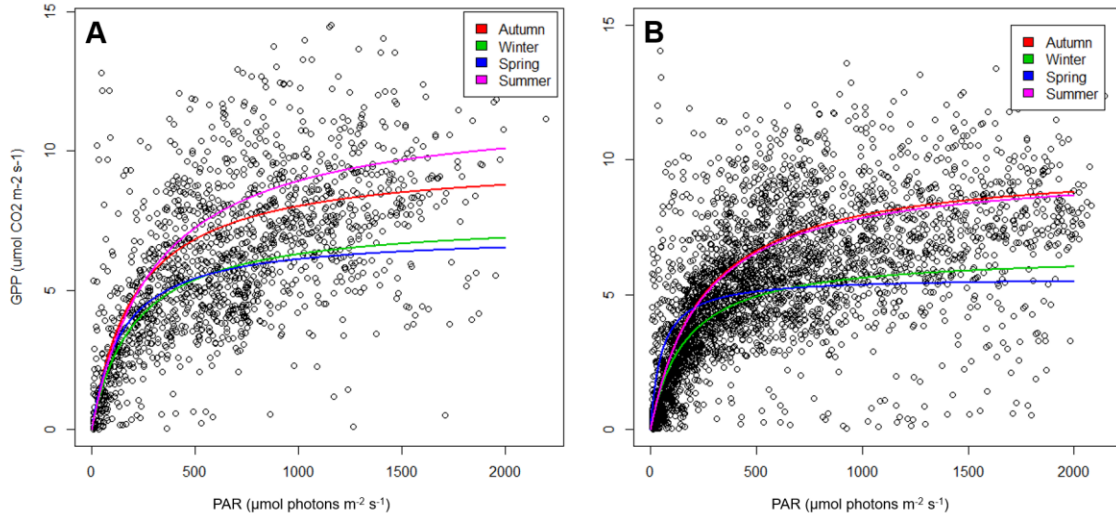


Figure 5. Relation of GPP and PAR in an anthropogenic peatland for different seasons, for A) conservation use, and B) agricultural use. Points represent 30-minute periods. Parameters of hyperbolic models are presented in Table 2.

Table 2. Parameters of seasonal hyperbolic models of GPP and PAR in an anthropogenic peatland with conservation and agricultural land use ( $p < 0.05$  for all models).

Land Use	Season	$\alpha$	$\beta$	$R^2$
Conservation	Autumn	9.70	209.90	0.53
	Winter	7.58	204.85	0.46
	Spring	7.01	146.54	0.23
	Summer	11.60	301.11	0.48
Agricultural	Autumn	9.88	245.62	0.70
	Winter	6.52	161.11	0.48
	Spring	5.64	51.59	0.19
	Summer	9.73	243.19	0.48

Air temperature showed a positive relationship with GPP for both types of land use (Fig. 6), however, this micrometeorological driver explained a lower percentage of the GPP variability than PAR. GPP in the agricultural land use section side was more sensitive to changes in temperature than the section under conservation (greater slope).

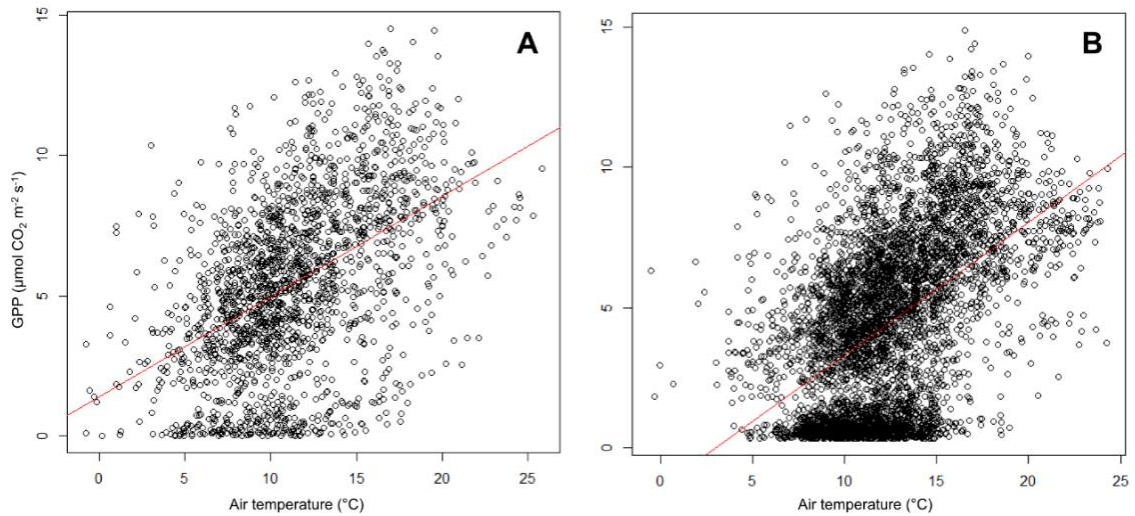


Figure 6. Relation of GPP and air temperature in an anthropogenic peatland. A) Conservation land use section ( $GPP = 0.356 * T_{air} + 1.412$ ;  $R^2=0.23$ ;  $p<0.05$ ). B) Agricultural land use section ( $GPP = 0.455 * T_{air} - 1.679$ ;  $R^2=0.27$ ;  $p<0.05$ ). Points represent 30-minute periods.

Ecosystem respiration showed exponential and significant relationships with  $T_{air}$  and  $T_{soil}$ . As these variables are strongly correlated ( $R>0.5$ ), only the relation of  $R_{eco}$  with  $T_{soil}$  is showed in Fig. 7. The range of temperature for  $R_{eco}$  was similar between both types of management in the anthropogenic peatland, but  $R_{eco}$  in the agricultural management side was slightly more sensitive to changes in temperature than the conservation side.

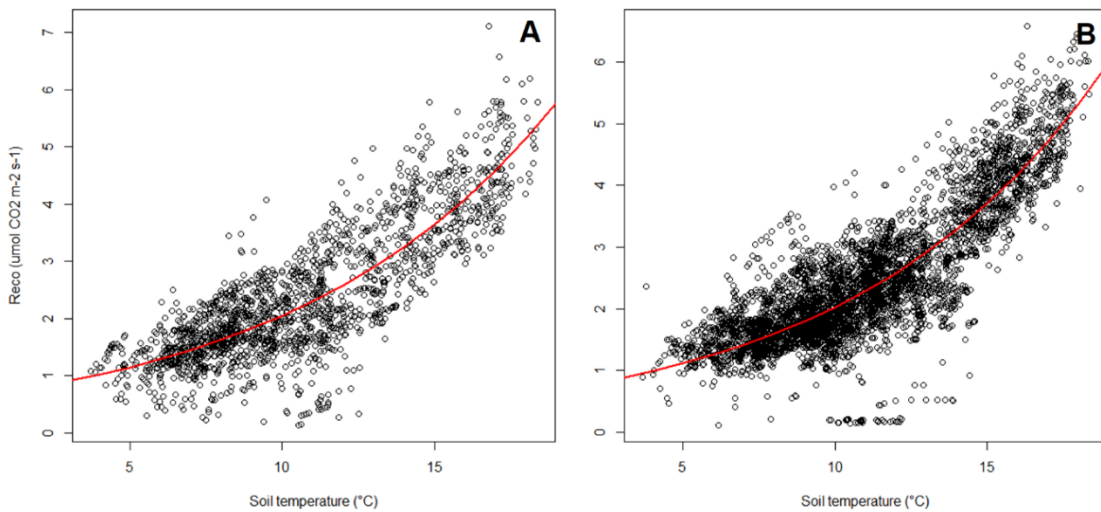


Figure 7. Relation of  $R_{eco}$  with  $T_{soil}$  in an anthropogenic peatland. A) Conservation land use section ( $R_{eco} = \exp(-0.440 + 0.116 * T_{soil})$ ;  $R^2=0.71$ ;  $p<0.05$ ). B) Agricultural land use section ( $R_{eco} = \exp(-0.498 + 0.121 * T_{soil})$ ;  $R^2=0.75$ ;  $p<0.05$ ). Points represent 30-minute periods.

Also,  $R_{\text{eco}}$  showed a negative and significant relationship with WT and SWF (Fig. 8 and Fig. 9). The magnitude of  $R_{\text{eco}}$  increased under drier conditions. The sensitivity of the  $R_{\text{eco}}$  flux to water availability in the soil (WT and SWF) was similar for both types of use in the anthropogenic peatland. Nevertheless, the percentage of  $R_{\text{eco}}$  variability explained by these environmental variables ( $R^2 < 0.55$ ) was lower than that explained by temperature ( $R^2 > 0.70$ ).

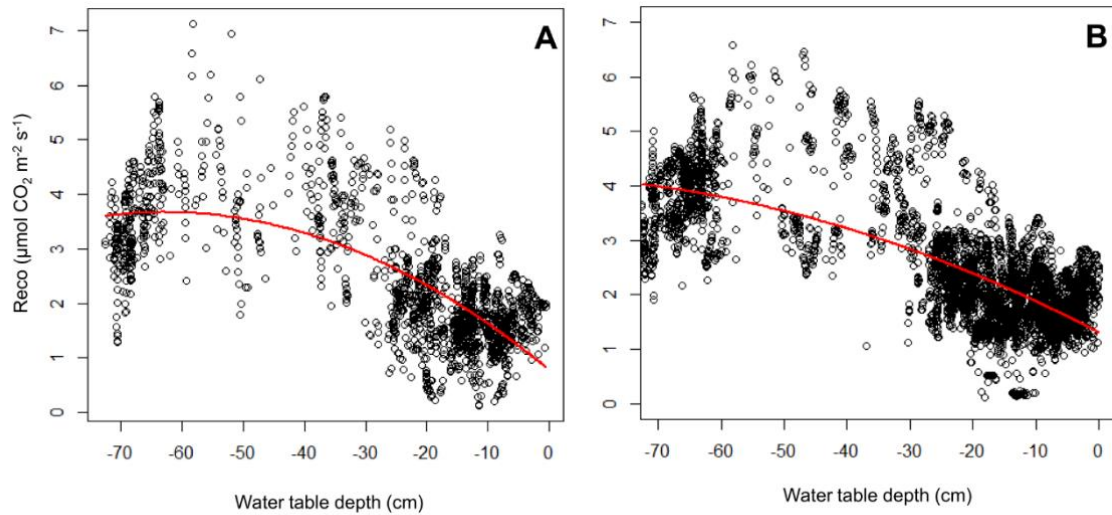


Figure 8. Relation of  $R_{\text{eco}}$  and WT in an anthropogenic peatland. A) Conservation land use section ( $R_{\text{eco}} = 0.007 * WT^2 + -0.092 * WT + 0.778$ ;  $R^2=0.51$ ;  $p<0.05$ ). B) Agricultural land use section ( $R_{\text{eco}} = -0.003 * WT^2 + -0.061 * WT + 1.303$ ;  $R^2=0.54$ ;  $p<0.05$ ). Points represent 30-minute periods.

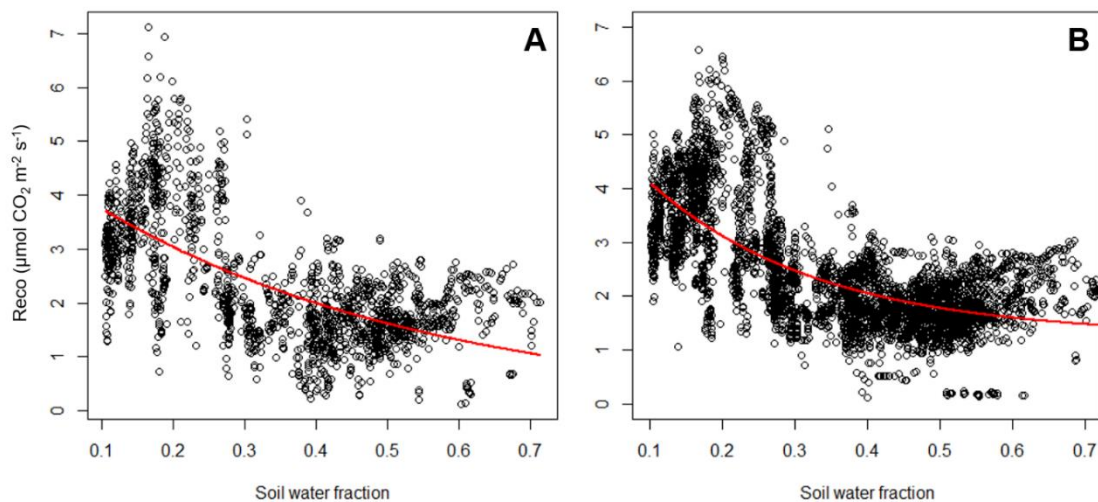


Figure 9. Relation of  $R_{\text{eco}}$  and SWF (at 5 cm of depth) in an anthropogenic peatland. A) Conservation land use section ( $R_{\text{eco}} = 4.620 * \exp(-2.104 * SWF)$ ;  $R^2=0.41$ ;  $p<0.05$ ). B) Agricultural land use section ( $R_{\text{eco}} = 1.261 + 4.363 * \exp(-4.276 * SWF)$ ;  $R^2=0.48$ ;  $p<0.05$ ). Points represent 30-minute periods.

## 4. Discussion

### 4.1 Seasonal fluctuations of carbon fluxes

GPP and  $R_{\text{eco}}$  showed a strong seasonality, with higher fluxes during spring and summer, and lower fluxes during autumn and winter. The peak of GPP in the peatland coincides with the maximum PAR, whereas the peak of  $R_{\text{eco}}$  coincides with the driest period of the year (low WT and SWF). La Fleur et al. (2003) reported similar variability for Canadian ombrotrophic bogs. Maxima of GPP and  $R_{\text{eco}}$  occurred consecutively during summer (December 2015 to March 2016) with a small difference between them. The magnitude of mean daily  $R_{\text{eco}}$  measured in this young anthropogenic peatland (7.92 and 4.82 g CO<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup> for agricultural and conservation sections respectively) is close to the range reported for older peatlands with 3.8 to 15.2 g CO<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup> and 9.8 to 20.5 g CO<sub>2</sub> m<sup>-2</sup> day<sup>-1</sup> for a Canadian ombrotrophic peatland (Lafleur et al. 2005) and a Polish mesotrophic peatland (Juszczak et al. 2013).

The transition observed in this anthropogenic peatland from a weak source of CO<sub>2</sub> during autumn and winter, to a strong sink of CO<sub>2</sub> during spring and summer, has also been observed in temperate peatlands in Sweden (Lund et al. 2012). The decrease in the magnitude of the GPP and  $R_{\text{eco}}$  during the winter has been reported for other peatlands (e.g., LaFleur et al. 2003) as a result of the senescence that vascular plants experienced during autumn (Aurela et al. 1998). In the anthropogenic peatland of Chiloé Island, the most frequent plant species *Myrteola nummularia* and *Gaultheria mucronata* (Cabezas et al. 2015), are both deciduous shrubs, which tend to have senescent foliage in late summer or autumn (from March to May).

### 4.2 Environmental drivers of fluxes

The positive relations found for GPP with T<sub>air</sub> and T<sub>soil</sub> coincide with the behavior of Scottish (Helfer et al. 2005) and Swedish temperate peatlands of natural origin (Peichl et al. 2014). Unlike previous studies, we did not find a significant relation between GPP and WT in the anthropogenic peatland. This lack of correlation could be explained because of the low soil depth, which implies less fluctuation in the water table depth (72 cm) in comparison to other types of peatlands.

Relation of GPP and PAR showed a sort of hysteresis between the seasons of the year, same as Helfer et al. (2015) observed for temperate peatlands from central Scotland. In contrast, the anthropogenic peatland from Chiloé Island showed a higher maximum GPP during autumn than in spring. This could be related to the fact that WT remains close to the soil surface during the winter and the slow sprouting of new leaves in the senescent vascular shrubs, which thus limits the biological activity and the efficiency of light use for photosynthesis. Maximum GPP coefficients in the anthropogenic peatland of Chiloé Island are high compared to Northern Hemisphere peatlands (Table 3). Moreover, the maximum GPP was higher in the section of the peatland under conservation land use than in the section of peatland currently under agricultural use. According to Peichl et al. (2018), these

differences in light saturation coefficients could be explained by the presence of vascular plants that have a major contribution to peatland productivity, changing the maximum GPP and the type of GPP light response model. This effect becomes relevant for the CO<sub>2</sub> sequestration, in the context of the heterogeneous plant cover composition previously reported for these anthropogenic peatlands (Díaz et al. 2008; Cabezas et al. 2015).

Table 3. Maximum GPP coefficient ( $\alpha$ GPP) in temperate and boreal peatlands.

Reference	Study site	Latitude	Type of peatland (Origin – Hydrogenetic)	$\alpha$ GPP ( g CO <sub>2</sub> m <sup>-2</sup> s <sup>-1</sup> )
This study	Chile	41°S	Anthropogenic – Minerotrophic (conservation land use)	9.0
This study	Chile	41°S	Anthropogenic – Minerotrophic (agricultural land use)	8.0
D’Acunha (2017)	Canada	49°N	Glacial - Ombrotrophic (under restoration)	5.0
Peichl et al. (2018)	Sweden	64°N	Glacial - Minerotrophic	1.9 to 4.4
Lund et al. (2015)	Norway	69°N	Glacial - Ombrotrophic	3.0 to 4.5

In the case of R<sub>eco</sub>, the strong positive relations with T<sub>air</sub> and T<sub>soil</sub> were expected because biological activity of plants and soil microorganism increase with temperature, and therefore enhance CO<sub>2</sub> emissions to the atmosphere. This behavior has been reported by several studies in North Hemisphere peatlands, including Christensen et al. (2012) for subarctic peatlands and Juszczak et al. (2013) for Polish temperate peatlands. The higher sensitivity of R<sub>eco</sub> to temperature in the agricultural section of the peatland could be related to the lower plant cover (62%), compared to the plant cover in the area under conservation use (87%) (Cabezas et al. 2015). Vegetation is also significantly lower in the agriculturally managed area; smaller and thinner coverage of plants leaves the soil more exposed to solar heating, favoring faster mineralization of organic matter.

The negative relations of R<sub>eco</sub> with WT and SWF agreed with previous studies. Lower water storage in the soil and an increase in the aerobic layer of soil profile favor the oxidation and decomposition of organic matter (Nykänen et al. 1998; Hendriks et al. 2007; Hooijer et al. 2010; Juszczak et al. 2013). The absence of difference in the response of R<sub>eco</sub> to SWF between both types of use could be explained by the proximity of WT to the soil surface, due to the low soil depth. However, this behavior could change in time due to the differences in volume and biomass of plants; if vegetation on the conservation management area keeps growing,

the soil could raise over the surrounding landscape and disconnect from the mineral source of soil water.

### **4.3 Annual carbon balance**

During the study period, regardless of the type of land use, the anthropogenic peatland functioned as a sink of CO<sub>2</sub>. Annual NEE in the anthropogenic peatland under agricultural use falls within the range described for other temperate and boreal peatlands studied in the Northern Hemisphere (Table 4). In contrast to conservation section of the anthropogenic peatland where NEE was higher in comparison to ombrotrophic peatlands in the North Hemisphere, however, was similar to minerotrophic peatlands in Poland (Table 4).

The larger NEE observed in the conservation land use could be explained by the larger cover of vascular woody plants, such as trees and shrubs, as part of the original remnant vegetation or pioneer recruitment. According to Cabezas et al. (2015), cover of shrubs in the conservation section of this anthropogenic peatland is 19%, compared to 11% in the agricultural land use area.

Table 4. Annual net ecosystem exchange (NEE) in temperate and boreal peatlands.

Reference	Country	Latitude	Type of peatland (use)	NEE (g CO <sub>2</sub> m <sup>-2</sup> year <sup>-1</sup> )
This study	Chile	41°S	Minerotrophic (conservation)	-759.9
This study	Chile	41°S	Minerotrophic (agricultural)	-258.1
Roulet et al. (2007)	Canada	45°N	Ombrotrophic	-410 to -7.3
Lafleur et al. (2003)	Canada	45°N	Ombrotrophic	-279 to -37
Sottocornola and Kiely (2005)	Ireland	51°N	Ombrotrophic	-223.7 to -180
McVeigh et al. (2014)	Ireland	51°N	Ombrotrophic	-293.3 to -117.3
Fortuniak et al. (2017)	Poland	53° N	Minerotrophic	-980 to -560
Dunn et al. (2007)	Canada	55°N	Ombrotrophic	-77 to 150.3
Helfer et al. (2015)	Scotland	55°N	Ombrotrophic	-495 to -19.1
Lund et al. (2012)	Sweden	56°N	Ombrotrophic	-108 to 87
Nilsson et al. (2008)	Sweden	64°N	Minerotrophic	-99 to -73.3
Peichl et al. (2014)	Sweden	64°N	Minerotrophic	-289.7 to -154
Johansson et al. (2006)	Sweden	68°N	Ombrotrophic	-103 to -89.1*
Aurela et al. (2002)	Finland	69°N	Minerotrophic	-68
Christensen et al. (2012)	Sweden	69°N	Ombrotrophic - minerotrophic	-348.3 to -308

\* fluxes measured only during growing season.

According to the climate change prediction made by Cabré et al. (2016), the average annual temperature will increase, and precipitation will decline in North Patagonia, which could change the magnitude of carbon fluxes and the carbon balance of the peatland. For example, an increase in WT depth could enhance  $R_{eco}$ . In a peatland mesocosm experiment, Bridgman et al. (2008) found greater carbon losses from peatland soils under drier conditions. This effect could be greater in anthropogenic peatlands under agricultural land use, because of the lower cover of vascular plants and its higher sensitivity of GPP and  $R_{eco}$  to temperature. A simple calculation using the equations that describe the relation of  $R_{eco}$  and GPP with micrometeorological variables (see Fig 6, 7 and 8), suggest that a reduction of 20% in precipitation and the consecutive increase of water table depth (see more details in the Appendices) will increase the magnitude of  $R_{eco}$  flux several times (Table 5). Also, an increase of 3°C in the annual mean temperature will increase the fluxes of GPP and  $R_{eco}$ , however, the effect on GPP should be greater than  $R_{eco}$  (Table 5). Such changes could even transform the peatland from a carbon sink to a source. Moreover, as the length of the dry

season increases, so does the risk of wildfires that could release stored carbon to the atmosphere (Limpens et al. 2008).

Table 5. Effect of climate change in  $R_{\text{eco}}$  and GPP fluxes ( $\text{g CO}_2 \text{ m}^{-2} \text{ day}^{-1}$ ) from the anthropogenic peatland

Variable	Scenario	Conservation land use				Agricultural land use			
		$R_{\text{eco}}$	Increase ratio	GPP	Increase ratio	Reco	Increase ratio	GPP	Increase ratio
Temperature	Increase 3°C	13.63	2.83	23.45	3.41	13.89	1.75	16.73	2.13
Precipitation	Reduction 20%	42.85	8.89	NA	NA	24.15	3.05	NA	NA

Even though we found that the anthropogenic peatland is a sink of  $\text{CO}_2$ , this flux represents 87% of the annual NEE of a temperate old-growth rainforest, as reported by Perez-Quezada et al. (2018) at the same location. Therefore, it is recommended to prevent activities such as clear-cutting and human-set fires that could transform native forests into anthropogenic peatlands (Díaz et al. 2007), because they decrease the amount of C stored and the rate of annual C fixation.

This is the first study of carbon fluxes and balance in a South American peatland, however, it is necessary to continue monitoring carbon exchanges for a longer period to capture the interannual variability and to assess the impacts of extreme weather events, such as seasonal frosts or droughts, on the balance of  $\text{CO}_2$  and other greenhouse gases. Moreover, the heterogeneous microtopography and variable plant composition of the anthropogenic peatland could contribute to the observed spatial variability in the fluxes of greenhouse gases, which should be documented at the microsite scale.

## 5. Conclusions

The anthropogenic peatland in our study site functioned as a net sink of  $\text{CO}_2$ , similar to other temperate peatlands in the Northern Hemisphere. However, current land use by local people generates differences in carbon fluxes and balance in this type of peatlands. We found that an anthropogenic peatland, where *Sphagnum* moss is been extracted and the soil and vegetation are disturbed by cattle grazing, can fix less carbon annually than the same peatland under conservation land use. Further, the  $\text{CO}_2$  fluxes are sensitive to changes in the environmental conditions, which is worrying considering the predicted changes in temperature and precipitation that are ongoing in Chiloé Island due to climate change. Although the anthropogenic peatland functions as a net carbon sink, its capacity to fix carbon is lower compared to temperate rainforests that grow in the same area. Consequently, disturbed areas where young anthropogenic peatlands are already established should be maintained and extractive activities should be regulated in order to enhance their carbon storage. To regulate and define limits for the practice of moss extraction, we need to estimate



the balance of greenhouse gases in anthropogenic peatlands subjected to different moss extraction and grazing intensities.

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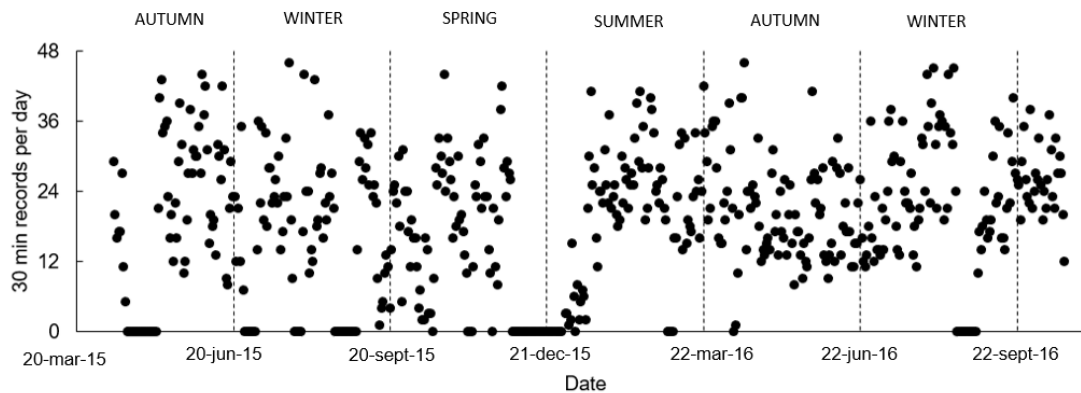
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## APPENDICES

Availability of 30-minute CO<sub>2</sub> fluxes records along the study period in the anthropogenic peatland



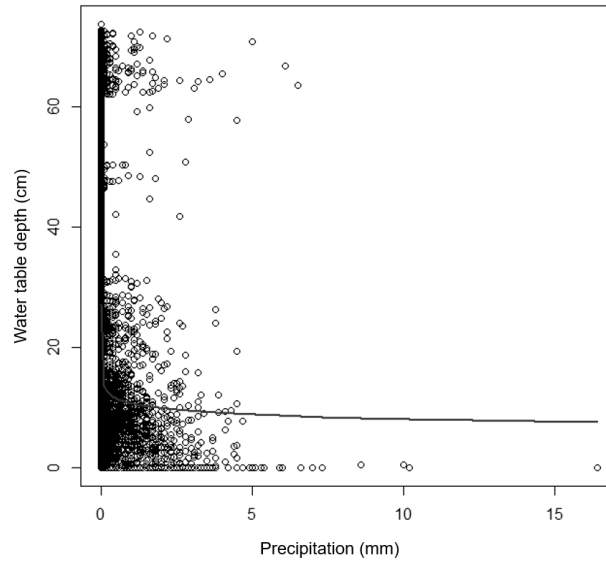
Frequency of the different size of gap in the 30 minutes record time series of CO<sub>2</sub> fluxes in the anthropogenic peatland

Type of gap	Quantity
1 hour	14004
1 day	96
1 week	9
1 month	1

}



Non linear model (exponential decay) used to estimate changes in WT depth (cm) in relation to precipitation (mm) ( $WT=1/(0.656+ \text{Precipitation}^{0.186}$ ;  $p<0.05$ ;  $R^2=0.1$ )



# EFFECTS OF AGRICULTURAL LAND USE ON THE GREENHOUSE GAS BALANCE IN AN ANTHROPOGENIC PEATLAND IN NORTHERN PATAGONIA

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## ABSTRACT

Peatlands are natural sources of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). Fluxes of these greenhouse gases (GHG) are sensitive to environmental changes. Anthropogenic peatlands in Chiloé Island are threatened by agricultural activities such as moss extraction and cattle grazing, which change soil conditions and vegetation. The relations between these variables and CH<sub>4</sub> and N<sub>2</sub>O fluxes are unknown for this type of peatlands. We measured CH<sub>4</sub> and N<sub>2</sub>O fluxes in an anthropogenic peatland using a dynamic transparent 1-m<sup>3</sup> chamber and a spectroscopic gas analyzer. The peatland is divided into two sections: one with conservation and one with agricultural land use. The relation of these fluxes with micrometeorological, vegetation and soil variables were tested. Besides, GHG balance was estimated for the sections under different types of land use. For CH<sub>4</sub>, conservation and agricultural area of the peatland acted as a source (0.97 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> and 2.93 mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> respectively). Methane fluxes were higher in microsites dominated by *Juncus procerus* and *Sphagnum* mosses in the agricultural land use section, which are frequently under waterlogged conditions. A positive relation was found between CH<sub>4</sub> fluxes and cover of aerenchymous plant *J. procerus*, and a negative relation was found with total N in soil. For N<sub>2</sub>O, conservation land use section was found to be sink (-0.99 N<sub>2</sub>O mg m<sup>-2</sup> h<sup>-1</sup>) whereas the agricultural section of the peatland acted as a source (0.21 N<sub>2</sub>O mg m<sup>-2</sup> h<sup>-1</sup>). However, differences of N<sub>2</sub>O fluxes between types of land use and vegetation were not statistically significant. Nitrous oxide fluxes did not show significant relations with environmental variables. Considering the CO<sub>2</sub> balance from a study carried out in the same peatland, the GHG balance showed that the conservation land use area acted as a sink (-1762.5 g CO<sub>2</sub> equiv m<sup>-2</sup> year<sup>-1</sup>) and the agricultural managed section acted as a source (294.0 g CO<sub>2</sub> equiv m<sup>-2</sup> year<sup>-1</sup>). Land use generated marked differences on vegetation structure and soil conditions in this anthropogenic peatland of Chiloé Island. These differences modify the GHG balance significantly in the anthropogenic peatland. Therefore, the current unregulated local practice of *Sphagnum* moss harvesting and cattle grazing on anthropogenic peatlands could generate a serious threat for local GHG balance.

Keywords: Chiloé Island, anthropogenic peatland, land use, methane, nitrous oxide.

## 1. Introduction

Peatlands are wetlands of international importance (Ramsar 2004), given their capacity to regulate and store significant volumes of water (Bullock and Acreman 2003), and also because they are large reservoirs and active sinks of carbon (C) (Gorham 1991). Peatlands are a natural source of greenhouse gases (GHG), such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>) and nitrous dioxide (N<sub>2</sub>O). Atmospheric concentration of CH<sub>4</sub> and N<sub>2</sub>O have increased significantly in the last century, reaching in 2011 around 1803 and 324 ppb, respectively (IPCC 2013). Moreover, CH<sub>4</sub> and N<sub>2</sub>O radiative forcing is 21 and 200 times that of CO<sub>2</sub>, respectively (Khalil and Rasmussen 1989; Shine et al. 1990), and have a lifetime of 10 and 150 years in the atmosphere, respectively (Khalil and Rasmussen and 1992).

In soils, CH<sub>4</sub> is produced by microbial activity in waterlogged conditions and is transported to the surface by diffusion, ebullition and through plant structures (Cicerone and Oremland 1988; Whiting and Chanton 1992). Recent studies have estimated that wetlands have a median global emission of 164 Tg CH<sub>4</sub> year<sup>-1</sup> (Bridgham et al. 2013).

Nitrous oxide is generated by two soil processes, namely nitrification (oxidation of ammonium to nitrate and nitrite) and denitrification (reduction of nitrate and nitrite to nitric oxide, nitrous oxide and dinitrogen) (Firestone and Davidson 1989). This gas is emitted in variable amounts depending on multiple soil conditions, such as soil water content, pH, carbon and concentration of N-oxides (Groffman et al. 2000).

Temperature increase stimulates CH<sub>4</sub> (Roulet et al. 1992) and N<sub>2</sub>O emissions (Blackmer et al. 1980; Huttunen et al. 2002). On the contrary, a strong negative relation has been reported between water table depth and CH<sub>4</sub> emissions in peatlands (Bubier 1995; Laiho 2006; Ojanen et al. 2010; Danevcic et al. 2010). Water table depth also changes N<sub>2</sub>O fluxes, however, the results are dissimilar (Melling et al. 2007). Martikainen et al. (1993) reported that largest N<sub>2</sub>O emissions in peatlands are generated in medium levels of water table depth, as a result of equilibrium between aerobic and anaerobic production processes. In contrast, other studies found that the largest N<sub>2</sub>O emissions are produced under lower water table levels, when the nitrification activity increases significantly (Zimenko and Misnik 1969; Williams and Wheatly 1999; Regina et al. 1996).

Variation in water-table could generate different microhabitats that produce changes in vegetation composition, thus relation between CH<sub>4</sub> and vegetation type also has been reported (Bubier et al. 1995; Schimel 1995; Ojanen et al. 2010). The presence of vascular plants with aerenchymous tissue could mobilize CH<sub>4</sub> and N<sub>2</sub>O from deeper layers of the soils to the atmosphere and contribute to the oxidation process (Whiting and Chanton 1993; Nilsson et al. 2001; Joabsson et al. 1999).

Nitrogen availability in soils could affect CH<sub>4</sub> and N<sub>2</sub>O fluxes, but this factor has been less studied and there is no consensus. Saarnio (2003) and Nykänen et al. (2003) did not find differences in fluxes after NH<sub>4</sub>-N and NO<sub>3</sub>-N addition. However, Klemetsson et al. (2005) and Ojanen et al. (2010) documented a strong relationship between N<sub>2</sub>O emissions and C:N

ratio; annual N<sub>2</sub>O emissions experimented an exponential decay with an increase in C:N ratio.

Although the relation between CH<sub>4</sub> and N<sub>2</sub>O fluxes and environmental conditions seems to be well described, all these studies are concentrated in the Northern Hemisphere. Thus, there is uncertainty about the behavior of southern peatlands. In Chile, peatlands are distributed from 39° to 55° of south latitude (Díaz et al. 2012). In this range of latitude, specifically on Chiloé Island, it is possible to find anthropogenic peatlands, which originated recently by forest logging or fires in places with high precipitation and poor-drainage soils (Díaz et al. 2008). Anthropogenic peatlands have heterogenous microtopography and vegetation composition that mix forest, wetland and grassland plants, including aerenchymous plant species (Díaz et al. 2008).

Locally, these peatlands are threatened by *Sphagnum* moss extraction and cattle grazing, activities that modify vegetation and soil conditions. Also, the north of Chiloé could experience strong changes due the climate change; by 2100 annual temperature will increase by around 3 °C and precipitation will decline by 10-20% (Cabré et al. 2016). The effect of this changes on CH<sub>4</sub> and N<sub>2</sub>O fluxes is unknown for anthropogenic peatlands.

The objectives of this study were 1) to estimate CH<sub>4</sub> and N<sub>2</sub>O fluxes in an anthropogenic peatland of Chiloé under conservation and agricultural land use, 2) to estimate the effect of land use, vegetation and environmental variables on the magnitude of CH<sub>4</sub> and N<sub>2</sub>O fluxes, and 3) to estimate the effect of land use on the GHG balance of an anthropogenic peatland.

## 2. Methods

### 2.1. Study area

The study area is in the north east of Chiloé Island, Los Lagos Region, Chile (Figure 1). The landscape is formed by a mosaic of Valdivian and Nord Patagonia temperate evergreen forest (Veblen et al. 1997), pastures and small croplands (Wilson & Armesto 1996). In this zone, the landscape is formed by patches of shrublands and anthropogenic peatlands covered by *Sphagnum* mosses (Díaz et al. 2008). The climate is temperate with a strong oceanic influence (Di Castri and Hajek 1976). Precipitations range from 2000 to 2500 mm, the minimum monthly temperature is 3°C (July), and the maximum temperature is 17°C (January) (Carmona et al. 2010). Soil is classified as “nadis” type (Veit and Garleff 1996) characterized for having an impermeable layer between 50 and 60 cm deep; this condition generated waterlogged soils during the winter (June to August).

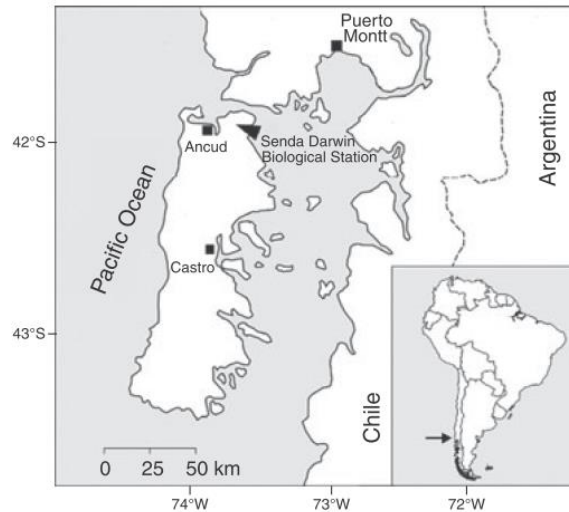


Figure 1. Study area located in Senda Darwin Biological Station, Chiloé Island, Chile.

The studied peatland is minerotrophic, with an area of approximately 16 ha and has two types of land use. One section of the peatland is under conservation land use (5.5 ha) where only tourism and scientific activities are practiced, which is part of the Senda Darwin Biological Station (SDBS) (41°S 56°E). The other section of the peatland is under agricultural land use (10.5 ha), where *Sphagnum* moss extraction and grazing are performed. The moss is extracted for commercial purposes (10 kg of dry moss per hectare per month) (Cabezas et al. 2015).

The vegetation has a heterogeneous composition, with the most frequent species being *Myrteola nummularia* y *Gaultheria mucronata*, mixed with *Sphagnum* mosses (Cabezas et al. 2015). Also, it is possible to find aquatic plants (e.g., *Juncus sp.* and *Apodasmia chilense*), forest understory species (e.g., *Blechnum magellanicum*, *Campsidium valdivianum*, *Eucryphia cordifolia* and *Tepualia stipularis*) and herbs from crops and pastures (e.g. *Aster vahlii*, *Centella asiatica* and *Ugni molinae*) (Díaz et al. 2008).

According to Cabezas et al. (2015), three vegetation microsites are present in the study site: a) areas dominated by *Baccharis patagonica* and *Sticherus cryptocarpa*, present only in the conservation land use section; b) areas dominated by *Juncus procerus* and *Sphagnum* mosses, present on both areas; and c) areas dominated by herbaceous species with no marked dominance, present only in the agricultural land use section.

Four sample points were placed on each vegetation microsite existing on each land use area (sixteen points in total) (Figure 2). Methane and N<sub>2</sub>O fluxes were measured in each point, where also vegetation, soil and micrometeorological variables were measured.

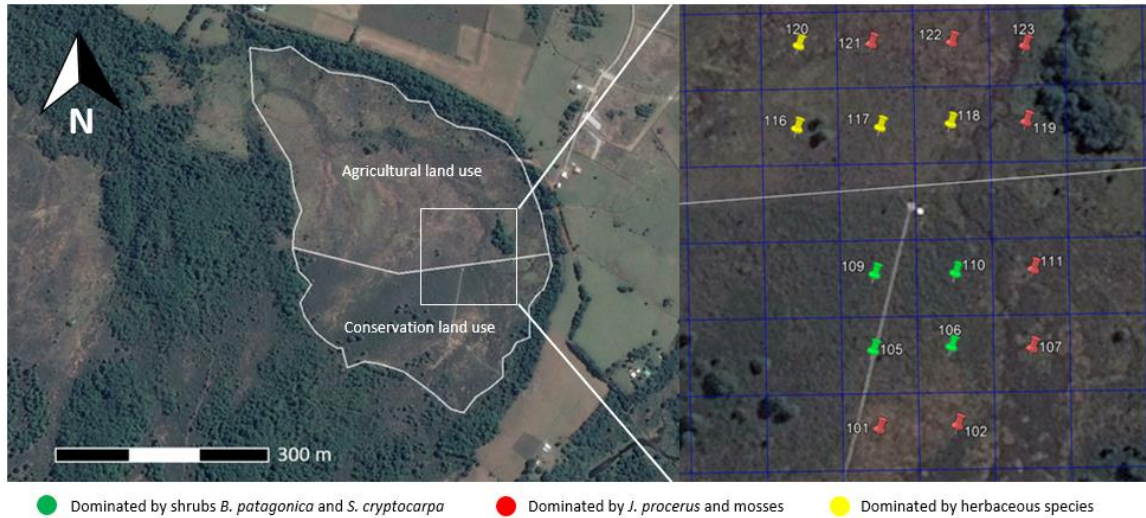


Figure 2. Location of sampling points in the anthropogenic peatland, placed both in the agricultural (north) and conservation (south) land uses.

## 2.2. Estimation of CH<sub>4</sub> and N<sub>2</sub>O fluxes

Methane and N<sub>2</sub>O concentrations were measured with a spectroscopic gas analyzer (PICARRO, G2308, Santa Clara, California, USA), connected to a transparent chamber (1 m<sup>3</sup>) made of PLEXIGLASS® polymer (Figure 3A). The chamber was placed onto aluminum frames of 1×1 m with a groove for water sealing (Figure 3B-D). In each sample point, two measurements per season were performed during one year (between spring-2015 and winter-2016). Measurement time window was 45 minutes, from which the first 5 minutes were discarded (purge period).

Gas fluxes were estimated using HMR package of R-project (Pedersen, 2017). The HMR package analyses the data series sequentially, and estimates CH<sub>4</sub> and N<sub>2</sub>O fluxes by fitting the concentration of each gas to a nonlinear function (Hutchinson & Mosier, 1981), using concentrated least square criterion:

$$C_t = \varphi + f_0 e^{-kt}, \text{ (Equation 1)}$$

where ( $k$ ) denotes concentrated least square, ( $f_0$ ) initial flux, ( $\varphi$ ) new chamber equilibrium concentration. If  $k$  tends to zero, the function was analyzed by a linear regression. For noisy concentration data with no clear trend and  $k$  tends to infinity, a zero flux was assumed.

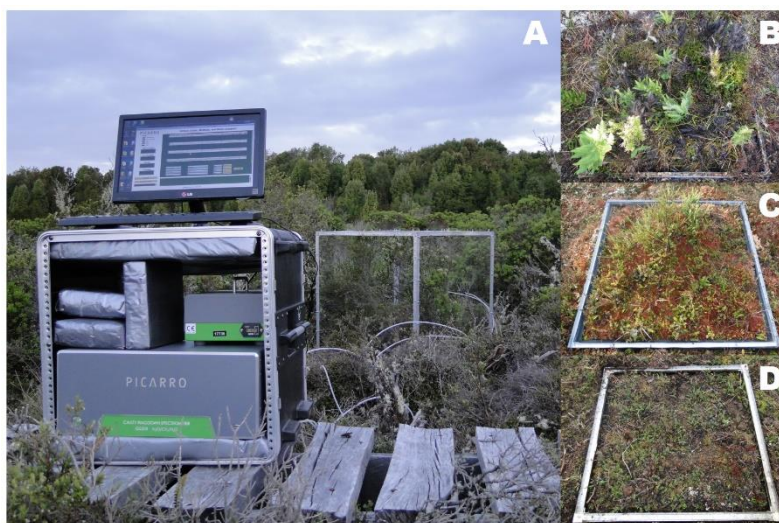


Figure 3. Devices for CH<sub>4</sub> and N<sub>2</sub>O measurements. A) Spectroscopic gas analyzer (PICARRO G2308) connected to the transparent static chamber. On the right, aluminum frames on microsites dominated by B) *B. patagonica* and *S. cryptocarpa*, C) *J. procerus* and mosses, and D) herbs.

### 2.3. Vegetation sampling

The plants inside each aluminum frame were identified and relative cover of plants was visually estimated, registering total cover of plants, vascular plants, non-vascular plants, and aerenchymous species *Juncus procerus* and *Carex magellanica*.

### 2.4. Soil sampling

On each sample point, soil depth was measured and two soil samples were extracted using a peat profile sampler (Eijkelkamp, Giesbeek, Netherlands). Samples were dried to calculate their weight and density. Total nitrogen content was estimated according to Kjeldahl method (Page et al., 1982) using an automatic digestion unit (K8, Behr, Germany) and a steam distillation unit (S1, Behr, Germany).

### 2.5. Micrometeorological variables

In parallel to CH<sub>4</sub> and N<sub>2</sub>O measurements, initial and final temperature inside the transparent chamber were estimated with a portable thermometer. Also, piezometers were installed to measure water table level depth at each sample point during flux measurements. Photosynthetically active radiation (PAR) was obtained from a meteorological station (LICOR, LI190SB model) placed in the anthropogenic peatland.

## 2.6. Greenhouse gas balance

Greenhouse gas balance was estimated using the average flux of CH<sub>4</sub>, N<sub>2</sub>O and CO<sub>2</sub> for the sections with different type of land use in the anthropogenic peatland. The mean annual flux of CH<sub>4</sub> and N<sub>2</sub>O were obtained from the measurements realized in this study and the mean flux of CO<sub>2</sub> was extracted from Valdés-Barrera et al. (in press) for the same peatland and study period. According to Chang et al. (2015) and Soussana et al. (2007), fluxes of CH<sub>4</sub> and N<sub>2</sub>O were converted to CO<sub>2</sub>-equivalent using the factors that represent the global warming potential (GWP, with inclusion of climate–carbon feedbacks) of each of these gases for a 100-year time horizon (IPCC, 2013). To estimate the GHG balance, mean hourly fluxes of CH<sub>4</sub> and N<sub>2</sub>O were upscaled to annual fluxes:

$$GHG\ Balance = CO_2\ flux + CH_4\ flux * GWP_{CH_4} + N_2O\ flux * GWP_{N_2O} \quad (\text{Equation 2});$$

where  $GWP_{CH_4} = 12.36$ , as 1 kg C-CH<sub>4</sub> = 12.36 kg C-CO<sub>2</sub>;  $GWP_{N_2O} = 127.71$ , as 1 kg N-N<sub>2</sub>O = 127.71 kg C-CO<sub>2</sub>; GHG balance was expressed in g CO<sub>2</sub>-equivalent m<sup>-2</sup> year<sup>-1</sup> (IPCC 2013).

## 2.7. Data analysis

Multifactorial ANOVA was performed to evaluate significant differences in environmental conditions and CH<sub>4</sub> and N<sub>2</sub>O fluxes between land use types, vegetation microsites and seasons of the year. Normality was tested using a Shapiro-Wilks test. To confirm which groups were dissimilar from another a Dunn's test was performed. Non-parametric correlation test (R-Spearman) was used to evaluate which environmental variable have significant relation with the fluxes of CH<sub>4</sub> and N<sub>2</sub>O. Statistical analyses were performed using R-project software (version 3.0.1).

# 3. Results

## 3.1. Micrometeorological variables

During the study period, water table depth showed significant differences between types of land use and vegetation in the anthropogenic peatland (Figure 4A). Water table was deeper in microsites dominated by *J. procerus* and mosses in the conservation land use area. Also, water table level showed high variability along the year (Fig. 4B). Average air temperature and PAR (Figure 5) showed significant differences between seasons, being significantly higher in summer (see more details in the Appendices).



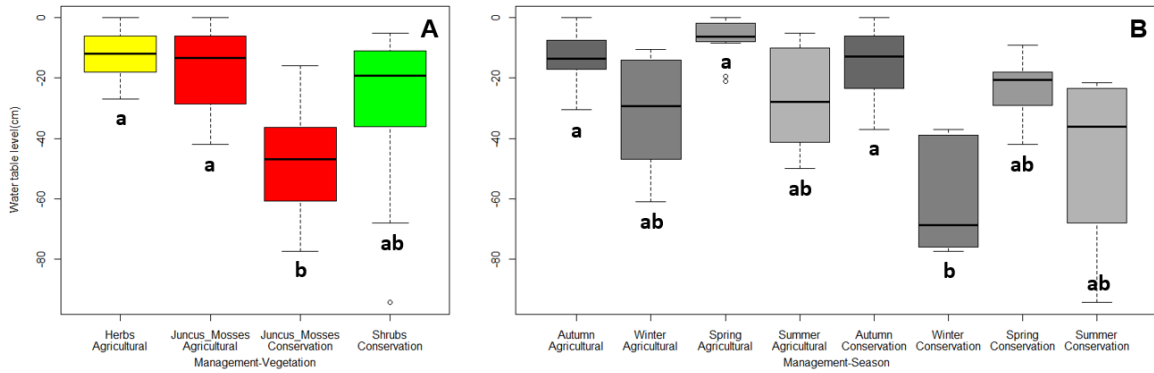


Figure 4. Comparison of water table depth in the anthropogenic peatland. A) Water table in microsites with different type of land use and vegetation. B) Water table level in different seasons of the year and types of land use. Colors represent different types of vegetation, letters indicate significant differences between the types of microsite and season.

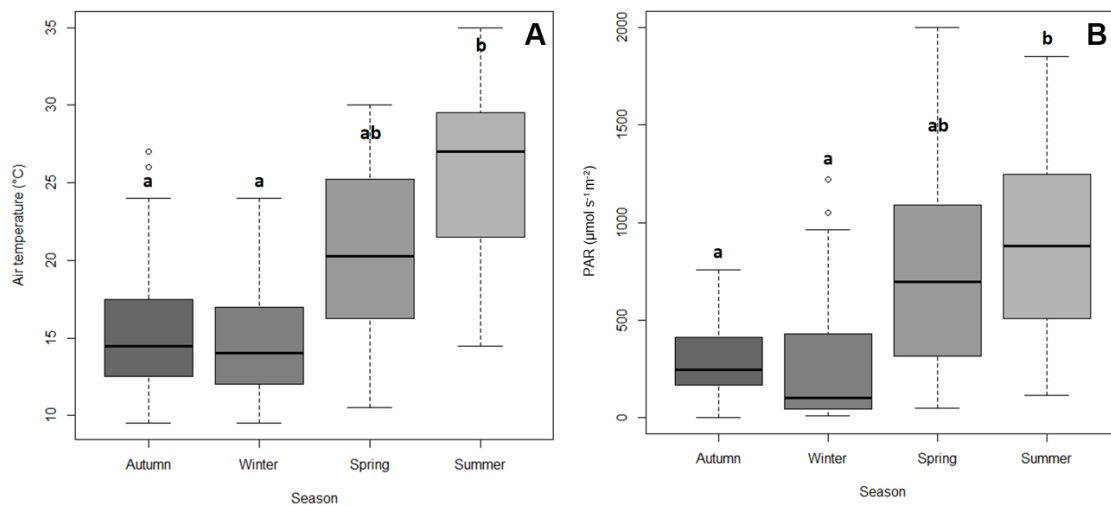


Figure 5. Comparison of air temperature and PAR between seasons in the anthropogenic peatland. Bars represent mean flux and standard deviation, letters indicate significant differences ( $p < 0.05$ ) between the seasons.

### 3.2. Soil and vegetation characterization

Soil depth and total nitrogen in soil had significant differences between type of land use and vegetation (Fig. 6A. and Fig. 6B. respectively). Soil depth was higher in microsites dominated by *J. procerus* and *Sphagnum* mosses in the conservation land use section and lower in microsites dominated by herbs on the agricultural land use section. Total nitrogen in soil was higher in conservation land use area and it was similar between the two types of vegetation within each land use type.

Land use and vegetation type showed significant differences in cover of *J. procerus* and *C. magellanica*. Relative cover of *Juncus procerus* ranged from 0 to 15% and it was higher in the microsites dominated by *J. procerus* and *Sphagnum* mosses in the agricultural land use area (Fig. 7A). Relative cover of *C. magellanica* ranged from 0 to 5% and it was higher in microsites dominated by *J. procerus* and mosses in the conservation land use section (Fig. 7B). Total plant cover was significantly higher in the area under conservation compared to the agricultural use area (Fig. 7C).

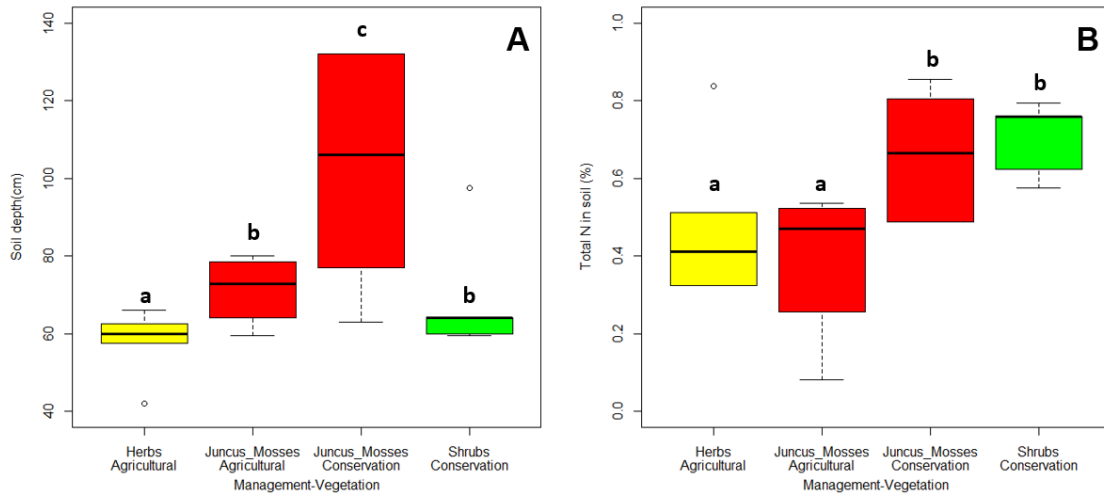


Figure 6. Soil characteristics in the anthropogenic peatland for sites with different types of land use and vegetation: A) soil depth and B) soil nitrogen content. Bars represent mean flux and standard deviation, letters indicate significant differences ( $p < 0.05$ ) between the types of microsites.

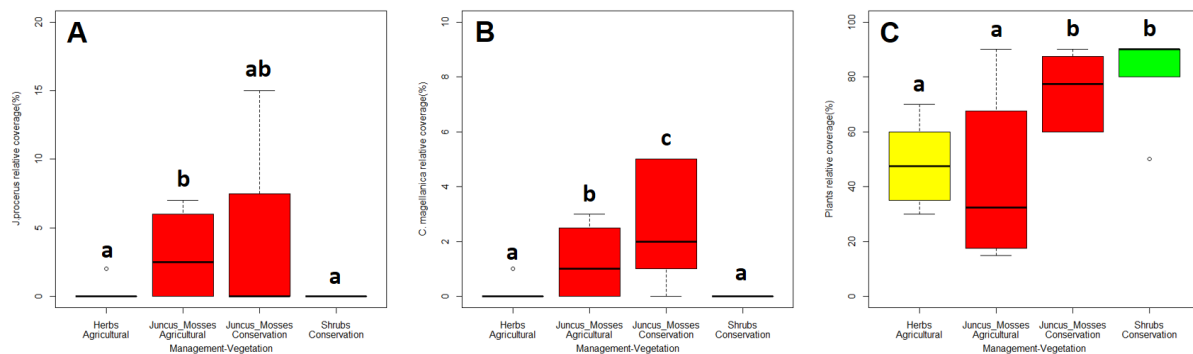


Figure 7. Plant cover in the anthropogenic peatland: A) cover of *Juncus procerus*, B) cover of *Carex magellanica*, and C) total plant cover. Bars represent mean flux and standard deviation, letters indicate significant differences ( $p < 0.05$ ) between the type of microsites.

### 3.2. Methane and nitrous oxide fluxes

Along the study period, the mean CH<sub>4</sub> flux in the anthropogenic peatland was  $0.97 \pm 0.03$  mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> for the conservation land use section, and  $2.93 \pm 0.05$  mg CH<sub>4</sub> m<sup>-2</sup> h<sup>-1</sup> for the agricultural land use area. In the case of N<sub>2</sub>O, mean flux for the area under conservation use was  $-0.99 \pm 0.04$  mg N<sub>2</sub>O m<sup>-2</sup> h<sup>-1</sup> and  $0.21 \pm 0.04$  mg N<sub>2</sub>O m<sup>-2</sup> h<sup>-1</sup> for the agricultural managed section. There were significant differences between seasons in CH<sub>4</sub> fluxes ( $p < 0.01$ , Figure 8A); for agricultural and conservation land use CH<sub>4</sub> fluxes were higher during the spring. Conversely, N<sub>2</sub>O increased progressively from autumn to spring, however, these differences between seasons were not significant ( $p > 0.5$ , Figure 8B) (see more details in the Appendices).

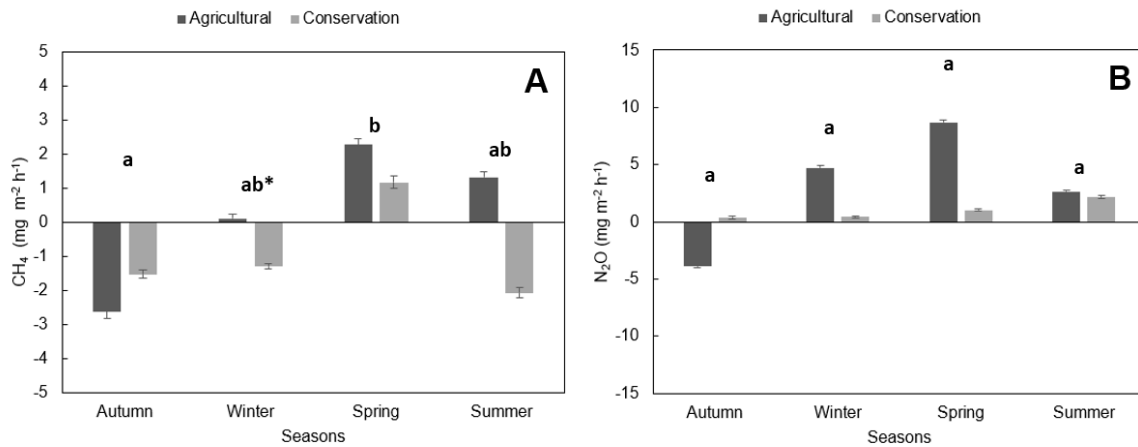


Figure 8. Methane and N<sub>2</sub>O fluxes (mg m<sup>-2</sup> h<sup>-1</sup>) for different types of land use and season of the year. A) CH<sub>4</sub> fluxes B) N<sub>2</sub>O fluxes. Bars represent mean flux and standard error, letters indicate significant differences between seasons and (\*) indicate significant difference between types of land use.

Land use and type of vegetation in the peatland generated significant differences between CH<sub>4</sub> fluxes. Microsites dominated by *J. procerus* and mosses in the agricultural land use site showed higher CH<sub>4</sub> fluxes (Fig. 9A). In contrast, there were no significant differences of N<sub>2</sub>O fluxes between type of land use and vegetation in the anthropogenic peatland (Fig. 9B).

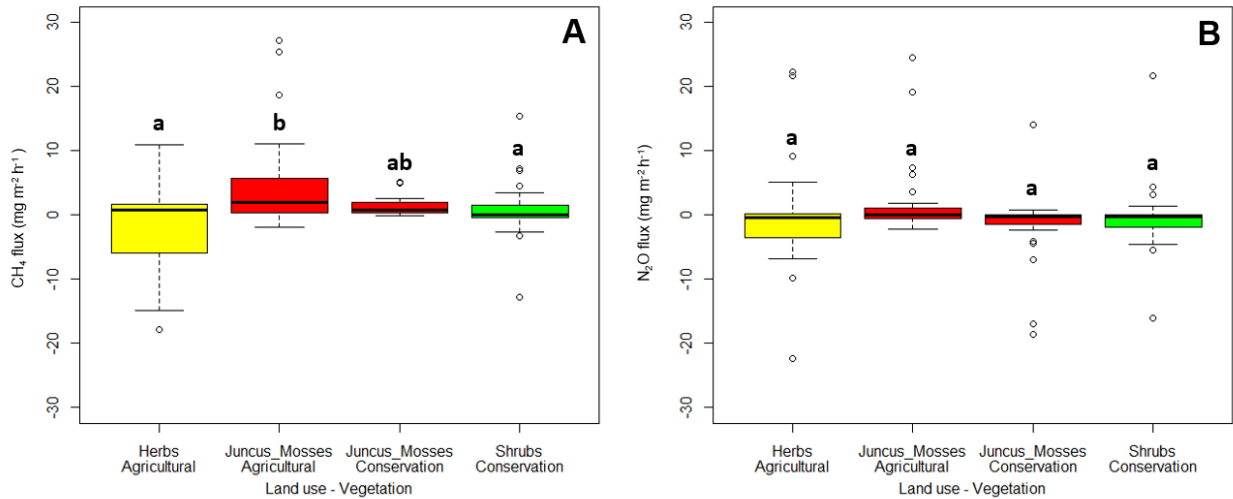


Figure 9. CH<sub>4</sub> and N<sub>2</sub>O average fluxes (mg m<sup>2</sup> h<sup>-1</sup>) in an anthropogenic peatland according to type of land use and vegetation. A) CH<sub>4</sub> fluxes B) N<sub>2</sub>O fluxes.

### 3.3. Effects of environmental variables on CH<sub>4</sub> and N<sub>2</sub>O fluxes

Fluxes of CH<sub>4</sub> in the anthropogenic peatland only showed a significant positive correlation with relative cover of *J. procerus* and a negative correlation with total nitrogen in soil (Table 1). In contrast, fluxes of N<sub>2</sub>O did not show significant correlations with the environmental variables measured in this study (Table 1).

Table 1. Correlation (R, Spearman coefficient) between CH<sub>4</sub> and N<sub>2</sub>O fluxes and environmental variables (n=64).

Environmental variables	CH <sub>4</sub> fluxes		N <sub>2</sub> O fluxes	
	R	p value	R	p value
Air temp	-0.076	0.383	0.077	0.392
Water table	0.096	0.310	-0.043	0.657
PAR	0.042	0.650	-0.022	0.814
Soil depth	0.001	0.987	-0.025	0.779
Total N	-0.155	0.077	-0.060	0.504
<i>Juncus</i> coverage	0.204	0.018	0.051	0.571
<i>Carex</i> coverage	0.063	0.473	0.006	0.946
Plant coverage	-0.064	0.469	-0.047	0.601

Significance code: (.) p<0.1; (\*) p<0.05.

### 3.4. GHG Balance

During the study period, there were notorious differences between fluxes from the different types of land use (Table 2). Conservation land use section acted as a sink of GHG and the agricultural land use section was a source. Moreover, the magnitude of the GHG balance in the conservation land use area of the anthropogenic peatland was six time bigger than the agricultural use area.

Table 2. Balance of GHG in the anthropogenic peatland

Land Use	CO <sub>2</sub> * (g CO <sub>2</sub> m <sup>-2</sup> year <sup>-1</sup> )	CH <sub>4</sub> (g CO <sub>2</sub> m <sup>-2</sup> year <sup>-1</sup> )	N <sub>2</sub> O (g CO <sub>2</sub> m <sup>-2</sup> year <sup>-1</sup> )	GHG Balance (g CO <sub>2</sub> m <sup>-2</sup> year <sup>-1</sup> )
Agricultural	-258.1	317.24	234.94	294.0
Conservation	-759.9	105.03	-1107.55	-1762.5

\*Valdés-Barrera et al. (in press)

## 4. Discussion

The anthropogenic peatland showed clear differences in soil conditions and plant cover depending on the type of land use. Agricultural land use showed lower plant cover and thinner soils, with a lower concentration of total N. These differences indicate that moss extraction and cattle grazing not only modify plant structure, but also generate soil compaction and erosion, even if these activities are practiced at small scale.

Fluxes of CH<sub>4</sub> in the anthropogenic peatland are within the range described for temperate and boreal peatlands (Table 3). Higher fluxes of CH<sub>4</sub> in microsites under agricultural land use and dominated by *Juncus procerus* and mosses, could be explained by the lower soil depth and water table level closer to the soil surface, which generates anoxic conditions along the year that favors CH<sub>4</sub> production. Also, these characteristics explain that higher CH<sub>4</sub> fluxes were observed in spring, when water table remains close to the soil surface. The negative relation of CH<sub>4</sub> and soil nitrogen content had been reported before for other ecosystems and could be explained by the large inhibition effect of N-compounds over methanogenesis in anoxic wet soils (Klüber and Conrad 1998).

In general, emissions of CH<sub>4</sub> in the anthropogenic peatland were higher in microsites dominated by *Juncus procerus* and *Sphagnum* mosses. This situation differs from Turetsky et al. (2014), who found that higher CH<sub>4</sub> fluxes in wetlands are associated to places dominated by graminoid species. The most abundant presence of aerenchymous plants, *Juncus procerus* and *Carex magellanica*, in this type of vegetational microsite could explain this difference because these plants favor the diffusion of CH<sub>4</sub> from deep soil layers to the atmosphere (Chanton and Whiting 1995). According to Diaz et al. (2008), *Juncus* species are not proper of natural peatlands in Chiloé Island, but their presence in the anthropogenic peatland is a result of a colonization process from other wetlands and riparian ecosystems. Therefore, the

control of the settlement of *J. procerus* on anthropogenic peatland could be an efficient strategy to reduce the CH<sub>4</sub> emissions.

Table 3. Mean CH<sub>4</sub> fluxes in temperate and boreal peatlands.

Location	Latitude	Peatland	CH <sub>4</sub> flux (mg m <sup>-2</sup> h <sup>-1</sup> )	Reference
Chile	41°S	Anthropogenic (conservation)	0.97	This study
Chile	41°S	Anthropogenic (agricultural)	2.93	This study
Slovenia	45°N	Bog	0.03	Danevcic et al. 2010
Canada	46°N	Fen	5.96	Strack et al. 2004
Germany	47°N	Bog	0.83	Jungkunst and Fiedler 2007
Germany	47°N	Bog	1.54	Jungkunst and Fiedler 2007
Germany	47°N	Bog	4.21	Jungkunst and Fiedler 2007
Germany	47°N	Bog	5.83	Jungkunst and Fiedler 2007
Germany	47°N	Fen	2.00	Fiedler et al. 1998
Canada	48°N	Fen	40.46	Godin et al. 2012
Canada	48°N	Fen	26.96	Godin et al. 2012
Canada	48°N	Fen	0.40	Godin et al. 2012
Argentina	54°S	Bog	0.72*	Lehmann et al. 2016
Sweden	57°N	Bog	1.12	Von Arnold et al. 2005a
Sweden	57°N	Bog	1.45	Von Arnold et al. 2005b
Finland	61°N	Bog	2.06	Nykanen 2003
Finland	62°N	Fen	5.72	Nykanen 2003
Finland	67°N	Water saturated bog	0.32	Huttunen et al. 2002
		<b>Mean</b>	<b>6.23 ± 0.22</b>	

\*Average flux of CH<sub>4</sub> for summer season

Table 4. Flux of N<sub>2</sub>O in temperate and boreal peatlands.

Location	Latitude	Peatland	N <sub>2</sub> O flux (mg m <sup>-2</sup> h <sup>-1</sup> )	Reference
Chile	41°S	Anthropogenic (conservation)	-0.99	This study
Chile	41°S	Anthropogenic (agricultural)	0.21	This study
Slovenia	45°N	Bog	0.610	Danevcic et al. 2010
Sweden	57°N	Bog	0.013	Von Arnold et al. 2005a
Sweden	57°N	Bog	0.004	Von Arnold et al. 2005b
Finland	67°N	Water saturated bog	0.001	Huttunen et al. 2002
		<b>Mean</b>	<b>0.16 ± 0.14</b>	

Regarding N<sub>2</sub>O fluxes, agricultural land use side showed N<sub>2</sub>O fluxes inside the range described for Northern Hemisphere peatlands (Table 4). However, fluxes in the conservation land use side showed that this area acted as a sink of N<sub>2</sub>O, contrary to what has been observed in other peatlands (Table 4). This behavior could be related to the higher coverage and richness of vascular plants in the conservation land use side that imply a higher demand for nitrogen. Other studies in different types of wetlands (e.g. Windham-Myers et al. 2018; Moseman-Vatierra et al. 2011) found similar behavior and suggest that wetlands can turn into a sink of N<sub>2</sub>O when N is limiting. The knowledge about the microbial process underlying this phenomenon is scarce, however, Kolb and Horn (2012) found that acid tolerant Proteobacteria have the potential to consume N<sub>2</sub>O in wetlands soils. This mechanism has been also confirmed in rice fields using stable isotope <sup>13</sup>C-labeled that demonstrate N<sub>2</sub>O reduction (Ishii et al, 2011). Goldberg (2011) using the stable isotope <sup>15</sup>N found that N present on wetlands deep soil layers has been consumed from the soil surface (atmospheric N<sub>2</sub>O concentration).

The absence of statistical differences in N<sub>2</sub>O fluxes between different types of land use and vegetation could be related to heterogeneity of the microtopography and plant structure that generate a wide range of variation in the N<sub>2</sub>O flux between the different types of land use and vegetation over the anthropogenic peatland. Therefore, for future studies that estimate N<sub>2</sub>O fluxes in anthropogenic peatland, it is highly recommended to increase the number or measurements per season and to incorporate microtopography variation in the analysis.

In comparison with other wetlands, this anthropogenic peatland under conservation land use acted as a significant sink of GHG due mainly to the sequestration of CO<sub>2</sub> and N<sub>2</sub>O from the atmosphere (Table 5). This coincides with the study of Schier-Uijl et al. (2014) where peatland under agricultural land use acted as a source of GHG and peatland under restoration acted as a sink of GHG. Considering the scarce policy regulation on *Sphagnum* moss extraction and the absence of management plans to prevent ecosystem damage on anthropogenic peatlands (Díaz et al. 2012), agricultural use could be a great threat to the local GHG balance.

Table 6. GHG fluxes and balance in different types of wetlands

Type of wetland	Location	Latitude	CO <sub>2</sub> gCO <sub>2</sub> -equiv m <sup>-2</sup> year <sup>-1</sup>	CH <sub>4</sub> gCO <sub>2</sub> -equiv m <sup>-2</sup> year <sup>-1</sup>	N <sub>2</sub> O gCO <sub>2</sub> -equiv m <sup>-2</sup> year <sup>-1</sup>	GHG Balance g CO <sub>2</sub> -equiv m <sup>-2</sup> year <sup>-1</sup>	Reference
Anthropogenic peatland (Agricultural land use)	Chile	41°S	-258.1	317.2	234.9	294.0	This study
Anthropogenic peatland (Conservation land use)	Chile	41°S	-759.9	105.0	-1107.6	-1762.5	This study
Brackish marsh	USA	29°N	666.2	444.0	50.4	1160.6	Krauss et al. 2016
Freshwater marsh	USA	29°N	-1063.0	1885.2	-9.6	812.7	Krauss et al. 2016
<i>Typha</i> sp. wetland	USA	30°N	3586.0	850.4	-	-	Whithing and Chanton 2001
<i>Typha</i> sp. wetland	USA	30°N	4175.6	1186.6	-	-	Whithing and Chanton 2001
<i>Typha</i> sp. wetland	USA	37°N	3286.8	1344.8	-	-	Whithing and Chanton 2001
<i>Peltandra</i> sp. wetland	USA	37°N	4246.0	2175.4	-	-	Whithing and Chanton 2001
Coastal peatland	USA	38°N	-2065	797	-186	-1454	Windham-Myers et al. 2018
Undisturbed prairie wetland	Canada	51°N	-311.6	57.7	-	-	Bortolotti et al. 2015
Recently restored prairie wetland	Canada	51°N	-1084.1	50.5	-	-	Bortolotti et al. 2015
Older restored prairie wetland	Canada	51°N	-2601.7	960.0	-	-	Bortolotti et al. 2015
Grassland on peatland	Netherlands	52°N	401.5	206.4	102.2	474.5	Schrier-Uijl et al. 2014
Restored peatland	Netherlands	52°N	1387.0	237.3	102.2	-620.5	Schrier-Uijl et al. 2014
<i>Carex</i> sp. fen	Canada	54°N	1518.0	909.7	-	-	Whithing and Chanton 2001
<i>Carex</i> sp. fen	Canada	54°N	492.8	435.1	-	-	Whithing and Chanton 2001
<i>Carex</i> sp. fen	Canada	54°N	1003.2	731.7	-	-	Whithing and Chanton 2001
Semi natural bog	Scotland	58°N	-114.0	53.1	N.S.	-50.0	Levy and Gray 2015
<b>Mean</b>			<b>1039.3 ± 3.0</b>	<b>768.5 ± 1.7</b>	<b>11.8 ± 15.5</b>	<b>53.8 ± 140.4</b>	



## 5. Conclusions

Land use on the anthropogenic peatland generated clear differences on soil characteristic and plant structure. Agricultural land use reduced significantly the plant coverage and the soil is thinner and have lower content of nitrogen than the conservation land use section of the peatland.

The emission of CH<sub>4</sub> was higher in agricultural land use area of the peatland where the water table remains closer to the soil surface. Flux of CH<sub>4</sub> was higher in microsites dominated by *Juncus procerus* and *Sphagnum* mosses. This behavior could be explained by the coverage of *J. procerus*, an aerenchymous species that mobilize the CH<sub>4</sub> from the deeper soil layers. The control of *J. procerus* settlement and growing could represent an alternative to reduce CH<sub>4</sub> emission in anthropogenic peatlands.

Conservation section acted as a sink of N<sub>2</sub>O in contrast with agricultural managed area which acted as a source of N<sub>2</sub>O. However, there were no significant differences between N<sub>2</sub>O flux from different types of land use and types of vegetation. Moreover, there were no significant correlations with the environmental variables measured in this study that explain the magnitude of the N<sub>2</sub>O fluxes.

Land use generated marked differences on the GHG balance. Agricultural land use turned the anthropogenic peatland from a sink to a source of GHG. This effect could be a great threat to the local GHG balance due to the scarce regulation of agricultural practices on anthropogenic peatlands of Chiloé Island.

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## APPENDICES

Comparison of micrometeorological variables in different seasons of the year in the agricultural land use sections of the anthropogenic peatland.

Variable	Autumn			Winter			Spring			Summer			p
	Mean	SE	N	Mean	SE	N	Mean	SE	N	Mean	SE	N	
WT	-13.21	0.18	17	-6.72	0.15	16	-14.61	0.20	17	-23.71	0.18	17	.
Tsoil	15.15	0.13	17	14.75	0.13	16	16.66	0.11	17	25.71	0.12	17	**
Tair	12.92	0.00	1148	10.02	0.00	1482	11.85	0.00	869	16.47	0.00	1010	**
PAR	460.88	0.03	705	362.49	0.03	674	741.39	0.05	466	1007.02	0.03	785	*

Significance code: (.) p<0.1; (\*) p<0.05; (\*\*) p<0.01

Comparison of micrometeorological variables in different seasons of the year in the conservation land use sections of the anthropogenic peatland.

Variable	Autumn			Winter			Spring			Summer			p
	Mean	SE	N	Mean	SE	N	Mean	SE	N	Mean	SE	N	
WT	-30.89	0.24	18	-27.09	0.25	16	-61.17	0.27	16	-45.38	0.31	16	*
Tsoil	16.31	0.11	18	14.63	0.10	16	24.38	0.14	16	24.66	0.17	16	**
Tair	10.88	0.00	396	8.84	0.00	327	9.95	0.01	337	15.63	0.00	534	**
PAR	583.49	0.08	258	543.96	0.08	232	803.65	0.13	178	847.56	0.06	409	*

Significance code: (.) p<0.1; (\*) p<0.05; (\*\*) p<0.01



ANOVA of CH<sub>4</sub> and N<sub>2</sub>O fluxes according to seasons

CH <sub>4</sub> fluxes						
	Df	Sum Sq	Mean Sq	F value	p	
Land use	1	126	126.46	2.381	0.125	
Season	3	747	249.08	4.689	0.004 **	
Land use:Season	3	659	219.78	4.137	0.008 *	
Residuals	121	6587	54.36			
N <sub>2</sub> O fluxes						
	Df	Sum Sq	Mean Sq	F value	p	
Land use	1	45	45.02	0.948	0.332	
Season	3	232	77.37	1.629	0.186	
Land use:Season	3	81	27.14	0.572	0.635	
Residuals	98	5603	47.49			

Significance code: (.) p<0.1; (\*) p<0.05; (\*\*) p<0.01

ANOVA of CH<sub>4</sub> and N<sub>2</sub>O fluxes according to vegetation

CH <sub>4</sub> fluxes						
	Df	Sum Sq	Mean Sq	F value	p	
Land use	1	126	126.46	2.141	0.146	
Vegetation	2	432	216.20	3.660	0.029 *	
Land use:Vegetation	3	559	186.29	3.154	0.027 *	
Residuals	125	7561	59.07			
N <sub>2</sub> O fluxes						
	Df	Sum Sq	Mean Sq	F value	p	
Land use	1	45	45.02	0.957	0.330	
Vegetation	2	181	90.44	1.924	0.150	
Land use:Vegetation	3	226	75.30	1.602	0.193	
Residuals	122	5736	47.02			

Significance code: (.) p<0.1; (\*) p<0.05; (\*\*) p<0.01

## 5. GENERAL CONCLUSIONS

The type of land use in the anthropogenic peatland generates several differences on plant composition, vegetation structure and soils conditions. These changes have a significant impact on GHG fluxes and balance.

Peatland under agricultural and conservation land uses acted as a sink of CO<sub>2</sub>, however, agricultural land use reduced the sink capacity of CO<sub>2</sub> in the anthropogenic peatland and, for both types of land use, is lower than the native temperate rainforest, ecosystems that turned into anthropogenic peatland due to the human impacts. The main environmental drivers of CO<sub>2</sub> fluxes were PAR and temperature for GPP and water table and soil water content for R<sub>eco</sub>. Considering the sensitivity of CO<sub>2</sub> fluxes to the environmental drivers in the anthropogenic peatland, the ongoing climate change should have an even higher impact on C balance.

Land use also generated differences on CH<sub>4</sub> and N<sub>2</sub>O fluxes in this anthropogenic peatland. Agricultural area of the peatland was a higher source of CH<sub>4</sub> than the conservation section. Besides, conservation area acted as a sink of N<sub>2</sub>O in contrast to agricultural area that was a source of N<sub>2</sub>O. The difference on CH<sub>4</sub> magnitude is related to *Juncus procerus* cover that increase the CH<sub>4</sub> fluxes due to the aerenchymous tissue that mobilized gasses from the deep layers of soil and total N in soil that could have an inhibitor effect on methanogenesis process. No significant relation was found between N<sub>2</sub>O fluxes and the environmental variables measured in this study.

Agricultural land use turned the anthropogenic peatland from a sink to a source of GHG. This fact could represent an important threat on local GHG balance due to the scarce regulation in Chiloé Island over the agricultural activities such as *Sphagnum* moss extraction and cattle grazing. Therefore, to keep or improve the GHG local balance areas with anthropogenic peatlands should be maintained and agricultural activities should be regulated. To regulate and define limits, we need to estimate the balance of greenhouse gases in anthropogenic peatlands subjected to different *Sphagnum* moss extraction and grazing intensities.

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