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Recent rates of carbon and nitrogen accumulation in peatlands of Isla Grande de Chiloé-Chile

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Abstract

Background: Peatlands play a key role in the global carbon cycle; these contain one third of the world's soil organic carbon, equivalent to more than half the amount of carbon in the atmosphere. Nevertheless, these ecosystems have been scarcely studied in southern South America. The main objective of this paper is to evaluate the recent accumulation rates of carbon (C) and nitrogen (N) in two kinds of oligotrofic peatlands in Isla Grande de Chiloé (Chile).

Results: Using peat C and N content, dry bulk density, and Pb-210 dating, we determined the rates of N and C accumulation in profiles from five peatlands in the northern Chilean Patagonia. The recent rate of C accumulation (RERCA) ranges from 8.5 to 87.06 g C m^{-2} $year^{-1}$, and the recent rate of N accumulation (RERNA) ranges from 0.15 to 2.37 g N m^{-2} $year^{-1}$. The difference in RERCA and RERNA between glacial peatlands and anthropogenic peatlands was significant. One of the remarkable results is that accumulation of N and C are directly related.

Conclusions: This study contributes for a better understanding of the Patagonian peatlands of Chile. In addition, this research contributes by setting a basis for conducting further studies and for assessing the impacts of climate change on peatlands.

Keywords: Carbon accumulation; Nitrogen accumulation; Northern Patagonia; Oligotrophic peatlands; Pb-210

Background

A distinct characteristic of peatland ecosystems is a disequilibrium between primary production and decay; c. 2% to 16% of the biomass produced annually forms peat (Tolonen and Turunen 1996). In these habitats, the rate of carbon (C) sequestration in natural peatlands is larger than the total rate of C losses; therefore, their C stock continues to increase (Joosten and Couwenberg 2008). Peatlands have in the past 15,000 years withdrawn enormous amounts of carbon dioxide (CO_2) from the atmosphere and stored it in their peat deposits (Yu et al. 2003; Joosten and Couwenberg 2008). They play a key role in the global carbon cycle and are influenced by global climate change. These habitats account for 3% to 6% of the Earth's land surface and contain around 600 gigatonnes of C (Charman 2002; Charman et al. 2013; Clymo et al. 1998). This means that peat represents about one third of the total global soil C pool. It contains an equivalent of approximately two thirds of all C in the atmosphere and the same amount of C as all terrestrial biomass on earth (Joosten and Clarke 2002). Peatlands are the most space-effective carbon stocks of all terrestrial ecosystems. In the (sub)polar zone, peatlands contain on average at least 3.5 times per ha, in the boreal zone 7 times, and in the tropical zone 10 times more C per ha than all other ecosystems (Joosten and Couwenberg 2008).

Peatlands are unusual in greenhouse scenarios because they sequester the major greenhouse gas, CO_2, from the atmosphere as peat. Nevertheless, on the other hand, they emit to it in large quantities both CO_2 and the second most important greenhouse gas, CH_4. Despite occupying a relatively small area of the earth's surface, 3% of the land and freshwater surface of the planet, these ecosystems process significant amounts of CO_2, CH_4, H_2S, and N_2O from the atmosphere. However, they can also become potential emitters of CO_2 and CH_4 if some of the factors involved in the development and dynamics of these ecosystems are destabilized. In this case, the potential impact of peatlands on the greenhouse effect and

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climate change would be decisive (Pontevedra Pombal et al. 2004). When the normally wet peat soils are in contact with the air, these soils begin to oxidize and decompose, releasing CO_2 (Joosten and Couwenberg 2008). Some estimations indicate that peatland degradation contributes up to 0.8 gigatonne C per year (Trumper et al. 2009). Peat accumulation shows a strong local and regional variation, and peat accumulation rates are dependent on climatic, hydrologic, and hydrochemical conditions (Joosten and Couwenberg 2008). In this sense, nitrogen (N) deposition may also affect C accumulation through effects on plant productivity and rates of organic matter decomposition (Turunen et al. 2004; Limpens and Berendse 2003).

C accumulation in peat can be estimated by different methods and time scale. One of the methods is the recent rate of carbon accumulation (RERCA), and this refers to the fresh peat that is annually added to the peatland system (Joosten and Couwenberg 2008; Rydin and Jeglum 2006). This quantization is based on the column section between the surface and a given dated horizon in a surface core. Data of bulk density, C content, and chronologies are used (Tolonen and Turunen 1996).

In Europe, North America, and China there have been conducted numerous studies on recent carbon dynamics in peatland (Gorham 1991; Turunen et al. 2004; Tolonen and Turunen 1996; Pitkänen et al. 1999; Bao et al. 2010; Ali et al. 2008; Pontevedra Pombal et al. 2004). Nevertheless, similar studies are scarce in southern South America. In Chilean Patagonia, vast expanses of peatland can be found. A significant number of peatlands were formed by peat accumulation in open water after glacial retreat (Villagrán 1991; Villagrán 1988; Heusser 1984), referred to in this paper as glaciogenic peatland. Nevertheless, in northern Patagonia, the use of fire and clearcutting since the middle of the 19th century in places with low drainage have created areas of wetlands dominated by species of the genus *Sphagnum* L. (Díaz et al. 2008; Zegers et al. 2006). When *Tepualia stipularis* (Hook. & Arn.) Griseb. forests on poorly drained soil are burned or cleared, waterlogged conditions impair the recolonization of forests and stimulate *Sphagnum* colonization (Díaz et al. 2007; Díaz and Silva 2012). These sites have been referred to as secondary or anthropogenic peatlands (Díaz et al. 2008).

The rate of C sequestration in peatlands is a crucial element in understanding the global C cycle and has been estimated on different timescales to ascertain the role of peatlands in global warming in the context of rising atmospheric CO_2 (Bao et al. 2010; Joosten and Clarke 2002). Added to this is that a better management of ecosystem carbon stocks and fluxes can substantially contribute to reducing atmospheric greenhouse gas concentrations (Joosten 2011).

Therefore, considering the above background, the aim of this paper is to describe some aspects of C and N accumulation through a comparative analysis of RERCA and the recent rate of nitrogen accumulation (RERNA) in anthropogenic and glaciogenic peatlands of Isla Grande de Chiloé (Chile) and also to establish the relationship between these rates.

Methods

Study area

The study area is situated on the Isla Grande de Chiloé, Región de Los Lagos in Chile (42° to 43° S and 73° to 75° W). Chiloé's climate is wet temperate with a strong oceanic influence (di Castri and Hajek 1976). It has an annual mean temperature of 9.6°C (Carmona et al. 2010), and its annual rainfall ranges from 1,900 to 2,300 mm (CONAF 2009), reaching even between 5,000 to 6,000 mm in some areas (Pérez et al. 2003).

We selected five sites located in the northern and central parts of the island (Figure 1). Two kinds of *Sphagnum* peatlands were studied, which were defined according to their origin and their characteristic vegetation (Díaz et al. 2008). The first type, glaciogenic peatland, was originated after the last glaciation. The second type, anthropogenic peatland, corresponds to flooded areas colonized by *Sphagnum* moss after the burning or logging of forests in areas with poor drainage soils (Zegers et al. 2006; Díaz et al. 2008). The two study areas representing the glaciogenic peatland type were Los Caulles (CA) and Púlpito (PL), and the three study areas representing the anthropogenic peatland were Senda Darwin (SD), Río Chepu (CH), and Teguel (TG).

Core samplings

The oligotrophic peatlands sampled were constituted of *Sphagnum* peat mainly of *Sphagnum magellanicum* Brid. In each locality, we took a short peat monolith (30 × 30 × 45 to 50 cm) with a sharpened metal sheet tin following the recommendations of De Vleeschouwer et al. (2010). The monoliths of peat were carefully extracted, wrapped in foil paper, and transported flat in rigid cases to be fractioned in subsequent hours. Approximately 4 to 5 cm from the outer layer of each monolith was removed to discard the material that was altered in the extraction and transportation. The monoliths were divided into intervals of 1 to 2 cm with a stainless steel saw.

Each segment was separated into two sub-samples: a small portion of 2 cm^3 to calculate bulk density and the other one with the rest of the material. These samples were deposited in polyethylene bags and stored at 4°C. The analyses were performed on some sections of the monoliths in non-continuous depths.

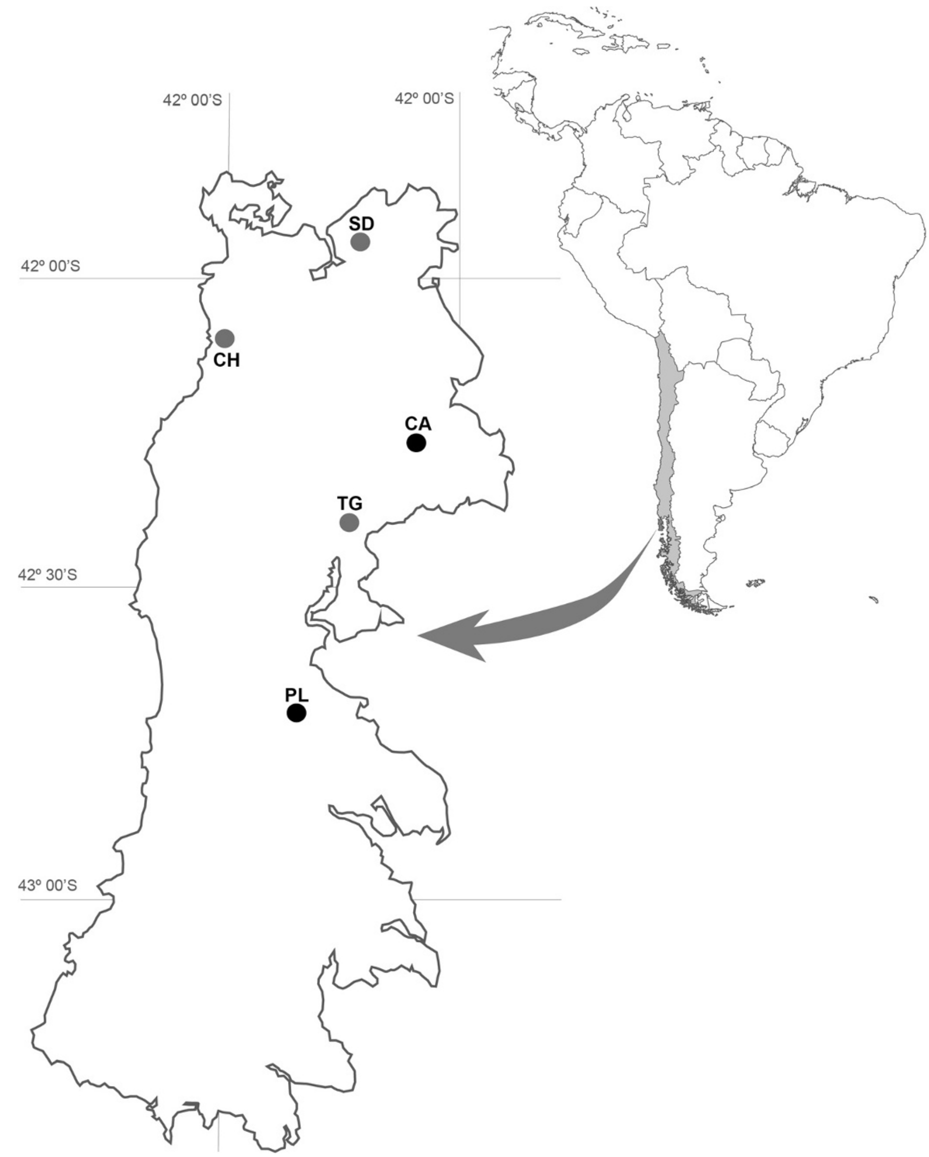

Figure 1 Study sites on Isla Grande de Chiloé. Glaciogenic peatlands: PL, Púlpito; CA, Caulles. Anthropogenic peatlands: SD, Senda Darwin; CH, Río Chepu; and TG, Teguel.

Physicochemical analysis

Water content and dry bulk density were obtained from weight loss by drying of a known volume of peat section at 105°C for 12 h. The first one was calculated from the mass difference and the second one was calculated from stable weight and known volume (Martínez Cortizas et al. 2009; Bao et al. 2010; Sadzawka et al. 2006; Wang et al. 2004). Ash and organic matter content were determined by calcination at 550°C for 6 h in a muffle furnace (Martínez Cortizas et al. 2009; Bao et al. 2010; Sadzawka et al. 2006; Wang et al. 2004). Following the procedures of Tolonen and Turunen (1996), Clymo et al. (1998) and Bao et al. (2010), organic C content was calculated by multiplying the organic matter content by 0.50. N content was analyzed by complete combustion at 950°C using an elementar analyzer and following the protocol USDA (1996). C/N ratio was established as the ratio of total C and total N. Calcination and C/N ratio were performed at *Centro de Espectrometría Atómica* of *Universidad Complutense de Madrid* (Spain) and *Laboratorio de Suelo* of *Instituto de Investigaciones Agropecuarias* (Chile).

Radiometric measurements and data analysis

The activities of Pb-210 were measured by gamma-ray spectrometry using hyper-pure germanium detectors in all areas sampled. However, in CAU and PUL, the concentration of Pb-210 activity decreased to the limits of detection. In these localities, descendants of Pb-210 and

Po-210 were measured with alpha spectroscopy using passivated ion-implanted silicon (PIPS). These analyses were performed at *Servicio de Radioisótopos* of *Universidad de Sevilla* (Spain). The Constant Initial Concentration (CIC) model of Appleby and Oldfield (1978) and Sánchez-Cabeza and Ruiz-Fernández (2012) was applied to calculate the ages of peat layers.

We estimated RERCA and RERNA following the Bao et al. (2010) model which used g dry bulk density, age, and C or N contents, as appropriate.

STATISTICA 7.0 (StatSoft 2004) was used for statistics analysis. The normality of variables was evaluated by the Shapiro-Wilk and Kolmogorov-Smirnov tests. Pearson correlations between RERCA and RERNA were calculated. We used one-way ANOVA to compare C and N accumulation between glaciogenic and anthropogenic peatlands.

Results

Water content and dry bulk density

The water content of the peat samples ranged from 735% to 1,927%, with outliers (206% and 327%) in the samples of SD. In SD and CA, a slight decrease of water content was observed in the deeper layers (Figure 2A). In the other localities, the water content shows slight variations along the depth.

The ranges of dry bulk density were 0.0100 to 0.065 g cm^{-3}. In SD, the dry bulk densities increased with depth. In contrast, we observed the opposite trend in CH; the density decreases to deeper layers. In the other three sites, the dry bulk density shows no significant variations along the profiles (Figure 2B).

Radioisotope chronology

In SD, TG, and CH peatlands, the activities (Bq kg^{-1}) (Figure 2C) of Pb-210 and Ra-226 were well-defined. However, in CA and PL from the third sample of each core, the activity decreased to the limits of detection of the technique. The activity was detected until 21 to 29-cm depth in glaciogenic peatlands and 28 to 37 cm in anthropogenic peatlands. Table 1 shows the chronologies (years AD) inferred from the Pb-210 using the CIC model.

C, N and C/N

The calculated organic C values show differences among localities. The higher mean values ± SD were observed in PL (50.03% ± 2.05%, n = 3), CA (47.3% ± 3.74%, n = 3), and CH (46.93% ± 1%, n = 3). The other two sites reported slightly lower mean values: TG (44.8% ± 1.8%, n = 3) and SD (39.6% ± 7.23%, n = 4) (Figure 2D). The mean values of the C content were higher in glaciogenic peatlands.

The percentage of N varied between 0.74 and 2.28. The highest mean values ± SD were reported in CH (1.93% ± 0.3%, n = 3) and PL (1.9% ± 0.58%, n = 3); secondly, CA (1.26% ± 0.34%, n = 3), and then SD (0.93% ± 0.19%, n = 4) and TG (0.83% ± 0.21%, n = 3) (Figure 2E).

The ranges of C/N ratios were 21.59 and 67.93. The highest mean values ± SD were found in TG (56.3 ± 12.1, n = 3) and SD (43.7 ± 10.2, n = 3), then CA (38.9 ± 6.8, n = 3), CH (24.5 ± 3.1, n = 3), and finally PL (28.1 ± 9.1, n = 3). In C/N ratio, we observed a slight trend to decrease at greater depths (Figure 2F).

RERCA and RERNA

The RERCA estimated are presented in Table 1. The location that showed the highest average rate ± SD was TG (58.18 ± 25.20 g C m^{-2} $year^{-1}$, n = 3), secondly CH (50.75 ± 15.40 g C m^{-2} $year^{-1}$, n = 3), then SD (32.77 ± 13.78 g C m^{-2} $year^{-1}$, n = 4), CA (15.45 ± 7.2 g C m^{-2} $year^{-1}$, n = 3), and finally PL (9.35 ± 3.02 g C m^{-2} $year^{-1}$, n = 3). It is noted that anthropogenic

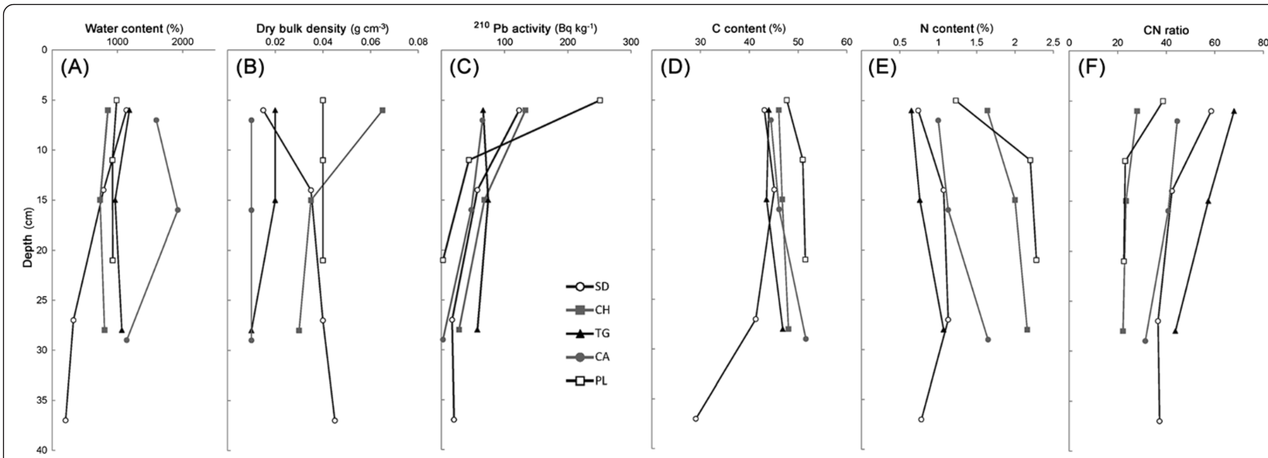

Figure 2 Variation of water content, dry bulk density, Pb-210 activity, C and N contents, and C/N ratio. Variations of **(A)** water content (%), **(B)** dry bulk density (g cm^{-3}), **(C)** Pb-210 activity (Bq kg^{-1}), **(D)** C content (%), **(E)** N content (%), and **(F)** C/N ratio, according to depth (cm). Localities: PL, Púlpito; SD, Senda Darwin; CH, Río Chepu; TG, Teguel; and CA, Caulles.

Table 1 Recent rates of C (RERCA) and N (RERNA) accumulation in the studied localities

Locality	Depth (cm)	Chronology (AD)	RERCA (g C m^{-2} $year^{-1}$)	RERNA (g N m^{-2} $year^{-1}$)
SD	6	1994	24.24	0.42
	14	1944	33.50	0.79
	27	1900	40.57	1.11
	37	1925	56.88	1.53
CH	6	1983	66.49	2.37
	15	1961	50.08	2.14
	28	1897	35.70	1.61
TG	6	1997	40.62	0.60
	15	1995	87.06	1.52
	28	1982	46.85	1.07
CA	7	1989	14.81	0.33
	16	1978	23.06	0.57
	29	1834	8.50	0.27
PL	5	1853	5.88	0.15
	11	1796	10.75	0.46
	21	1632	11.42	0.51

peatlands (TG, SD, and CH) have higher RERCA than glaciogenic peatlands (PL and CA) in the last 100 years. Moreover, there is a highly significant difference between the two types of habitats as reported by one-way ANOVA ($F1, 14 = 21.231$, $p = 0.0004$).

The Table 1 shows the estimated values of RERNA. The overall mean ± SD was 0.97 ± 0.68 g N m^{-2} $year^{-1}$ ($n = 16$). The location that presented the highest average rate ± SD was CH (2.04 ± 0.39 g N m^{-2} $year^{-1}$, $n = 3$), secondly TG (1.06 ± 0.46 g N m^{-2} $year^{-1}$, $n = 3$), and then SD (0.77 ± 0.47 g N m^{-2} $year^{-1}$, $n = 4$), CA (0.39 ± 0.15 g N m^{-2} $year^{-1}$, $n = 3$), and PL (0.37 ± 0.19 g N m^{-2} $year^{-1}$, $n = 3$).

According to the results of one-way ANOVA, a highly significant difference between mean RERNA of anthropogenic and glaciogenic peatlands was observed ($F1, 14 = 12.09$; $p = 0.0037$).

On the other hand, a strong, highly significant, and directly proportional relation ($r = 0.81$; $n = 16$; $p = 0.0001$) between RERNA and RERCA was observed. Figure 3 shows the Pearson's correlation.

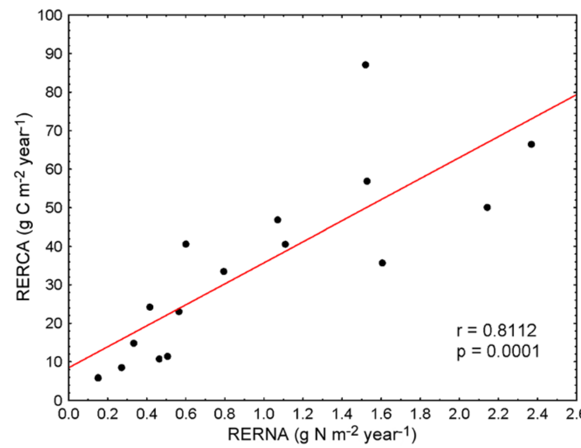

Figure 3 Relationship between RERNA and RERCA in peat profiles.

Discussion

Globally, our results showed that there is a difference between the two types of peatlands studied and throughout the period studied in the content and storage of C and N. Our study shows that glaciogenic peatlands present higher values of C content in relation to anthropogenic peatlands. This difference may be related to the trophic status of peatlands and the source of nutrients. Martínez Cortizas et al. (2009) reported that ombrotrophic peatlands have much higher proportions of carbon than minerotrophic peatlands. These results concur with León (2012) who found that some anthropogenic peatlands as SD have transitional characteristics between minerotrophic and ombrotrophic, in contrast to PL or CA that are clearly ombrotrophic.

In general terms, we also note that N% increased slightly in the first centimeters of the profiles. These results are consistent with other studies conducted in southern hemisphere islands where ombrotrophic peatlands with oceanic influence have nitrogen concentrations that increase progressively in the first centimeters deep, coinciding with the fluctuation zone above the water table (Damman 1988). This increase may be explained by the leaching of nitrogen from the well-drained higher layers (Damman 1988; Pontevedra Pombal et al. 2004). Kuhry and Vitt (1996) also show that nitrogen is lost from acrotelmo through denitrification, surface runoff, and erosion. Nevertheless, in bogs, most nitrogen is lost while being restrained in catotelmo.

According to our results, C/N ratio values were similar to those reported for peatlands of northwestern Spain with an average of 34 (Pontevedra Pombal et al. 2004) and near the range reported for ombrotrophic peatlands in southern Sweden (Malmer et al. 1997). Nonetheless, our results are well below the highest values found in Tierra del Fuego where ratios reach values over 250 (Kleinebecker et al. 2008). The C/N ratio has been considered as an important indicator of decomposition of organic matter (Martínez Cortizas et al. 2009). High-mean C/N ratios found in ombrotrophic peatlands have been attributed to the low microbial activity in *Sphagnum*-rich peat due to the decomposition resistance of this material and the lack of easily assimilated energy, leading to the lack of biotic degradation of the organic matter (Pontevedra Pombal et al. 2004).

On the other hand, mean values of RERNA fluctuated depending on the site (0.15 to 2.37 g N m^{-2} $year^{-1}$). These values are mostly within the ranges given for other geographic areas such as southern Sweden (2 g N m^{-2} $year^{-1}$) (Malmer and Holm 1984) or eastern Canada (1.4 to 3.2 g N m^{-2} $year^{-1}$) (Turunen et al. 2004). Nevertheless, in some sampled locations, significantly lower values were observed compared with those reported for the northern hemisphere. RERNA does not show a common pattern throughout cores: in two sites, RERNA increases with depth; in one site decreases; and in the other two sites increases and decreases. Therefore, to understand the variation of nitrogen, it is necessary to consider specific covariables for each study area, such as precipitation, temperature, and nitrogen atmospheric deposition, among others (Turunen et al. 2004).

We also noted that anthropogenic peatland sites (TG, SD, and CH) have higher accumulation rates of carbon during the last 100 years than glaciogenic peatland sites (PL and CA), which may indicate that anthropogenic peatlands, being novel ecosystems, are more active. Several studies in boreal *Sphagnum* peatlands shown that carbon accumulation rates are significantly higher in recent peat deposits, and the average carbon accumulation decreases over time by the slow decomposition that takes place in deeper and anoxic layers of peat (Tolonen and Turunen 1996; Turunen et al. 2004; Gorham 1991; Clymo et al. 1998). Nevertheless, it is important to note that the average of carbon percentage is higher in glacial peatlands, which would store carbon more efficiently.

The results of the five profiles do not show a general trend of increase or decrease in the carbon accumulation rates in relation to depth. Specifically, the observed trend changes depending on the site. The variation between the profiles could be attributed to intrinsic characteristics of the sites such as geological or climatic conditions, as well as variations of the sampling site nanotopography. Turunen et al. (2004) found a substantial variation in carbon accumulation between and within peatlands, depending if the profile had been extracted in mounds or depressions. This pattern was also reported by Økland and Ohlson (1998).

In an exploratory way, climatic variables with RERCA and RERNA were correlated. Precipitation and mean annual temperature data were obtained from the two closest meteorological stations to the study sites: Ancud (north side of the island) and Puerto Montt (63 km north of the island). Nonetheless, no significant correlation was observed. In our opinion, these results could be attributed to the lack of quality in the used data rather than to a non-significant correlation between accumulation and climatic conditions, as there is a lack of historical climate information on the island.

Furthermore, our results also show a strong and highly significant correlation between carbon and nitrogen accumulation rates, which is consistent with the patterns found by Moore et al. (2005). This important relationship can be understood considering that nitrogen is a limiting nutrient in these ecosystems (Malmer 1990) and that it is involved in productivity and rates of peat decomposition.

Conclusions

In this study, we have presented the recent accumulation rates of carbon and nitrogen from a type of ecosystem that has great influence on the global carbon balance. On the basis of these results, we noted the need for more detailed and accurate studies of chronologies in order to compare values of carbon accumulation with obtained data for other geographic areas. Similarly, there are important questions related to the influence of the deposition of atmospheric nitrogen on carbon accumulation and biomass production of *Sphagnum* and associated vascular plants. On the other hand, it is also highly relevant to continue the study of carbon dynamics in the Patagonian peatlands due to the high threat faced by the exploitation of peat and live moss and for the relevance these ecosystems have on climate change. Finally, this research also contributes by setting a basis for conducting further studies and for assessing the impacts of climate change on peatlands.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

CAL designed the study, performed research, analyzed data and wrote the paper. GOM designed the study, contributed to field work and manuscript development. Both authors read and approved the final manuscript.

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