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Discussions

Recent significant decline of strong carbon peat accumulation rates in tropical Andes related to climate change and glacier retreat

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Abstract. Climate change has altered precipitation and temperature patterns in the tropical Andes. As a result, tropical glaciers have retreated significantly over the past 50 years and have even disappeared in some areas. Andean peatlands, one of the most important Andean carbon reservoirs, also seem to be affected by these climate changes, since glaciers have been recognized as one of their vital water sources. Here, we point out the important role of Andean peatlands on carbon accumulation rates (CAR), one of the highest in the world, and the impact of climate on carbon storage over the last 65 years, using four peat cores. The peat cores were radiocarbon-dated and ages were post-bomb calibrated and chronological models indicated basal ages (30 cm depth) ranging from 1957 to 1972 CE, where accumulation rates reached up 1.7 cm yr^{-1}. For both peatlands, carbon accumulation rates are high (mean of 470 and 220 g C m^{-2} yr^{-1} at APA 1 and APA 2 sites, respectively) and can reach up to 1010 g C m^{-2} yr^{-1}. *Distichia muscoides* is the dominant species in the Peruvian Central Andes peatlands and the high CAR, among other factors, is a characteristic of this species. Our results point out that a marked decrease of CAR after the early 1980s at both peatlands is likely related to an increase in annual temperature, which is responsible for the retreat of glaciers. We use a new high-resolution proxy (Skrzypek et al., 2011) based on the δ^{13}C of *Distichia* along the cores to evaluate the temperature variability at the site. We observed a general trend of increase in the reconstructed temperature from both studied peatlands from 1.9 to 2 ℃ for the period 1970–2015 CE. Comparison with air temperature data from the NCEP-NCAR reanalysis for the higher resolution cores shows a good relationship and an increase of 2.15 ℃ for the same period. Temperature increase may directly affect CAR by an increase in organic matter degradation rates. The decrease in CAR during the period of study may also be due to a decrease in melt water inflow generated by the retreat of glaciers that have almost disappeared today in the catchments as a consequence of regional warming. Our findings emphasize that marked changes in carbon accumulation rates demonstrate the high ecological sensitivity of tropical high-Andean peatlands, endangering their outstanding role in the regional (and even global) C cycle as large C sinks that contribute to the mitigation of global climate change.

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1. Introduction

Peatlands are the largest organic carbon (C) terrestrial reservoirs, covering approximately 3% of the Earth's surface and
35 containing about 25% (600 Gt C) of the global soil C stock (Yu et al., 2010; Xu et al., 2018). The amount of C stored in
peatlands is similar to the total C stocks in all living biomass or in the atmosphere (Yu et al., 2016) and is equivalent to twice
the quantity stored in the global forest biomass (Pan et al., 2011). Even though peatlands worldwide play an important role in
the C cycle and many of them have been the focus of scientific researches, the C and vegetation dynamics of high-Andean
cushion-dominated peatlands are still poorly understood.

40 In Andean peatlands, cushion-forming vascular plants, dominated by *Distichia muscoides* (Schittek et al., 2018), are found in
areas with poor drainage or with a positive hydrological balance at very high elevations (Kleinebecker et al., 2010). They are
the dominant component of the vegetation of high-mountain peatlands of the Andes at elevations between 3500 and 5100 m
asl, due to its adaptability to the freezing conditions and harsh windy associated with high Andean ecosystems. High-altitude
tropical peatlands represent one of the most important water reservoirs, providing outstanding environmental services that
45 contribute to maintenance of biodiversity in the Andes and the welfare of local human populations (Chimner & Karberg,
2008; Salvador et al., 2014). Their most important ecological role is to accumulate organic C by controlling decomposition
processes in the soil (Muñoz García and Faz Cano, 2012; Cooper et al., 2015), but they are now among the ecosystems most
vulnerable to climatic changes (Charman et al., 2013). Recent study on Andean peatlands (Huaman et al., 2020) have shown
significant variations in C accumulation over the last 3000 years BP, which is correlated with the occurrence of extreme
50 precipitation events, moreover drier or wetter and/or warmer or colder phases are also related to periods of advance and/or
retreat of tropical glaciers.

More than 99% of the glaciers in the world's tropical latitudes are located in the central Andes, with 70% of them in Peru
(Chevallier et al., 2010). In the high Andes, climate change has altered precipitation and temperatures patterns (Rabatel et al.,
2013; Vuille et al., 2018). As a consequence, tropical glaciers have dramatically withdrawn over the past decades and have
55 almost disappeared in many areas (Jomelli et al., 2009; Rabatel et al., 2013; Vuille et al., 2008; 2018). Compared to glaciers
in temperate or polar regions, tropical glaciers are particularly sensitive to climate variations, as they are subject to
considerably higher levels of energy forcing because they are located at low latitudes and then at higher altitude. In addition,
the period of maximum precipitation coincides with summer, resulting in snow accumulation at the highest elevations, but
rapid melting at the lowest elevations because of the relatively high temperatures (Kaser and Ostmaston, 2002; Chevallier et
60 al., 2010).

In this context of global and regional climatic changes, with temperature on the rise and changes observed in the seasonal
distribution of precipitation (Vuille et al., 2018), the Peruvian Andes are particularly vulnerable as they contain little glacier
coverage and rely on seasonal water storage from wetlands and permafrost to recharge the headwaters (Vuille et al., 2003).
The sensitivity of glacier coverage is demonstrated by the trend in the changes in their mass balance, which has been quite
65 negative over the past 50 years, slightly more negative than the trend computed at a global scale. A break point in the trend

appeared in the late 1970s, when the retreat accelerated. Before that date, changes in glacier length were limited. Since the end of the 1970s, however, glacial withdrawal has increased, with the glaciers retreating at more than twice the rate of the former period, between 500 and 700m in length (Rabatel et al., 2013). This is especially negative for high-mountain peatlands in the Andes because tropical glaciers have been recognized as one of the main water sources for them,

70   maintaining a stable water table through the year (Thompson et al., 2006; Benavides et al., 2013).

In this study, we assessed the impact of climate change on high mountains peatlands in the Central Andes of Peru, pointing out negative consequences on one of the major C reservoirs not yet well known in the Andean region. We used a new paleoclimate proxy based on changes of C stable isotope to assess past temperature trends. Finally, these new information show how environmental and climate changes and its effects (as the accelerated glacial withdrawal) can affect peatlands and

75   also how altered peatlands can affect the carbon cycle in the future.

2. Study Area

Two tropical high-elevation peatlands (APA 1, 4200 m asl and APA 2, 4420 m asl) were studied in Apacheta region in the central Andes of Peru, between 13° 20' S and 13° 21' S, and 74° 39' W and 74° 40' W (Fig. 1). APA 1 is located in a sub-catchment with an area of 130 km^2, with an elevation ranging from 4200 to 5000 m asl, while APA 2 sub-catchment had an

80   area of only 2.5 km^2, with an elevation ranging from 4350 to 4850 m asl.

In this region, the vegetation is dominated by *Distichia muscoides* Nees & Meyen, a Juncaceae species present on most high-elevation peatlands in the central Peruvian Andes (Schittek et al., 2015). *D. muscoides* is a dioecious semiaquatic plant that grows in dense cushions (Buffen et al., 2009; Skrzypek et al., 2011; Schittek et al., 2018). It has an altitudinal vegetation limit between 3500 and 5100 m asl. *Distichia* leaves are 3 to 7 mm-long, are inserted densely along the stem and form hard

85   monticules (diameter: ~2 m), which are compact mats surrounded by flooded hollows that are permanently bare of vegetation (Balslev, 1996). This species is well adapted to the high-elevation Andean climate and is able to survive diurnal cycles of freezing and thawing (Buffen et al., 2009). *Distichia* cushions may have started to form as a single individual, producing a large number of shoots and rhizomes, which later transformed into smaller groups as the underground parts of the plant died off (Schittek et al., 2018).

90   The climate of the Apacheta peatlands is typical of tropical high mountains with little seasonal variations in temperature and large seasonal precipitation variability. Based on data from the Apacheta station located near the two Andean peatlands of this study, about 1.6 km, at 13° 20' 51" S, 74° 38' 44" W and 4150 m asl, the study area presents an average annual precipitation of 830 mm for the period 1991–2012 CE and is marked by seasonal precipitation, with the wettest months being from October to March (monthly average: 114 mm). This seasonal pattern of rainfall reflects the occurrence of South

95   American Monsoon during South Hemisphere summer. The mean annual temperature of the upper part of the basin is 6.4 ℃ for the period 2000–2014 CE, with monthly averages ranging from 4.8 to 7.6 ℃; and the annual average relative humidity is 70.3% (for the period 2009–2013 CE) (GORE Ayacucho, 2015).
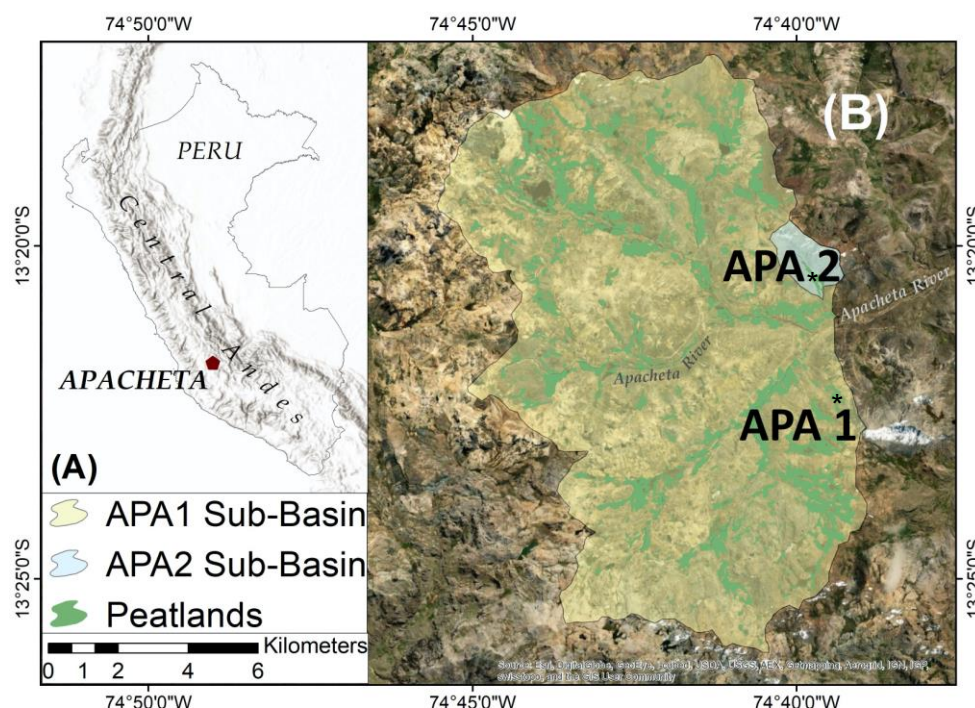
Figure 1: (A) Location of the study peatland area, Apacheta, in the Central Andes of Peru. (B) The sub-basins of the two peatlands are delineated, and the location of the peat cores in APA1 (4200 m asl.) and APA2 (4420 m asl.) are pointed by a black star (Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community).

3. Materials and Methods

For this study, four short peat cores between 29 and 35 cm-long were collected: APA1–C1 and APA1–C5 from the site located at an altitude of 4200 meters (APA 1), and, APA2–C3 and APA2–C4 from the other peatland at 4420 meters (APA 2) (Fig. 1). The peat cores were collected manually using PVC tubes 50 cm long and 8 cm in diameter, with sharpened edges to facilitate penetration and avoid compaction. Compression of the cores was minimal (or non-existent) because of the natural rigidity characteristic of the *Distichia* plant. The short cores were opened longitudinally in the laboratory. Soon after opening, the peat was sampled in aluminum U-channels to determine peat bulk density and water content. Sub-samples were taken at 1 cm intervals along the cores, and the water content was measured after oven drying at 50 °C for a few days to obtain a final stable weight. Bulk density (g cm^{-3}) was calculated by dividing the dry weight by the volume of these fresh sub-samples.

Samples were dated using an accelerator mass spectroscopy (AMS) at the "Laboratoire de Mesure du Carbone 14 (LMC14) - UMS 2572 (CEA/DSM CNRS IRD IRSN - Ministère de la Culture et de la Communication)" in Gif sur Yvette (France) and

at the Radiocarbon Dating Laboratory Beta Analytic in Miami, Florida (USA). All radiocarbon ages were modern (post-CE 1950), so they were calibrated using CALIBomb, available at http://calib.org/CALIBomb, which is based on a compilation of atmospheric ^{14}C based on comprehensive and reliable radiocarbon data derived from atmospheric samples and tree-ring series for the period from 1950 to 2010 CE (Hua et al., 2013). Because of the location of our study sites, the Shcal13.f14c

120 data set for Southern Hemisphere Zone 1 - 2 was applied. The age - depth model was built using Clam (Code non-Bayesian, 'classical' age - depth models) (Blaauw, 2010). The chronological models of all four short cores were determined using a smooth spline regression.

Peat sections (3 cm long) from each short cores were analyzed for organic matter (OM) concentration (%) by burning the samples in a muffle furnace at 550 °C for 5 hours (LOI: loss on ignition). TOC content of the peat samples was estimated

125 using the conversion formula (Eq. 1) for *Disticha muscoides* peatlands published by Cooper et al. (2015) (R^2: 0.92):

$$TOC\ (\%) = 0.53 * OM\ (\%),\tag{1}$$

C stable isotope composition (δ^{13}C in ‰) was determined using an isotope ratio mass spectrometer (Micromass Optima)

130 from the University of California-Davis (USA) and from the IRD-Bondy Research Center (France).

Carbon accumulation rates (CAR in g C m^{-2} yr^{-1}) were determined by multiplying the bulk density, accumulation rate and TOC content (Lähteenoja et al., 2009; Cooper et al., 2015; Xing et al., 2015).

We used new stable isotope paleoclimate proxy (δ^{13}C) based on a strong relationship found between the C stable isotope composition of *Distichia* and air temperature (Skrzypek et al. 2011). They found that the δ^{13}C value increases when

135 temperature decreases at about -0.97 ± 0.23‰/°C for Distichia peat (R^2: 0.86). This value was similar to the previously reported range for other species (included Sphagnum peat: -0.5 to -0.6‰/°C), and can be used to estimate relative paleotemperature changes recorded in Andean *Distichia* peat, as they mentioned.

Finally, we used the NCEP-NCAR reanalysis precipitation and temperature monthly data for the period 1948–2021 CE (at geopotential equals to 600 mb) for the zone that extend from 12º 30' S to 12º 54' S and 73º 30' W to 73º 95' W

140 (https://www.esrl.noaa.gov/) (Kalnay et al., 1996) for the climate analysis because in the study area there were no meteorological data for a continuous long time series covering at least the last six decades, necessary to compare the meteorological conditions with the analysis of the peat cores.

4. Results

Twelve ^{14}C dating (AMS) samples (Table 1) were used to determine the chronology for the four peat cores. For cores from

145 APA 1, the chronological model indicated a basal age of 1971 CE at 30 cm depth, while the ones from APA 2 dated to 1957 CE at the same depth (Fig. 2). All cores showed rapid growth rates of *Distichia*, with the highest values at the base (maximum value: 1.7 cm yr^{-1}) and an abrupt change occurred at the end of the 1970s, when the rates visibly decreased.

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Table 1: AMS ^{14}C data post-modern carbon (pMC) and calibrated ages (with 2 sigmas) of the four peat cores.

| Core	Laboratory Code	Core depth (cm)	pMC	Error pMC	Calibrated ages (cal years CE, 2 sigmas)
APA1–C1	Beta – 54412	3 – 4	105,73	0,2333	**2009**
	Beta – 54413	15 – 16	126,58	0,2607	**1982**
	Beta – 54414	30 – 31	143,77	0,2708	**1974**
APA1–C5	SacA43156	2 – 3	105,71	0,3829	**2009**
	SacA43157	12 – 13	119,94	0,3351	**1986**
	SacA43158	26 – 27	145,62	0,3717	**1973**
APA2–C3	Beta – 54415	2 – 3	106,09	0,2244	**2009**
	Beta – 465506	11 – 12	120,08	0,4500	**1986**
	Beta – 465507	32 – 33	104,32	0,3900	**1957**
APA2–C4	Beta – 54409	2 – 3	105,63	0,2870	**2009**
	Beta – 54410	16 – 17	123,01	0,2521	**1984**
	Beta – 54411	30 – 31	103,89	0,2373	**1957**
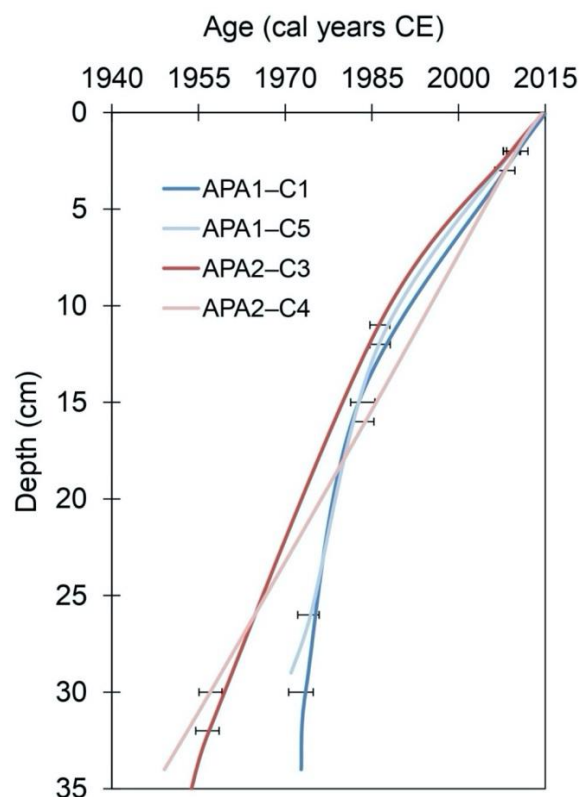
Figure 2: Age–depth models of peat cores (APA1-C1, APA1-C5, APA2-C3 and APA2-C4) based on post-bomb radiocarbon ages calculated with CALIB BOMB software ((http://calib.qub.ac.uk/CALIBomb/) using a smooth spline regression estimated by ClamR (Blaauw, 2010).

Mean bulk density (Supplementary Table 1) of the peat cores from APA 1 was 0.1084 g cm^{-3} (SD: 0.0499 g cm^{-3}). For the cores from APA 2 the average was 0.0767 g cm^{-3} (SD: 0.0242 g cm^{-3}). Both values were similar to those found in peatlands dominated by *Distichia muscoides* in Bolivia (Cooper et al., 2015).

In Peruvian peatlands, mean organic matter was very high (96% for APA1 and 92% for APA2) (Fig. 3). Mean TOC content resulted slightly greater for APA 1 than for APA 2 (51.0% and 48.6%, respectively) (Supplementary Table 1). However, there was a general upward trend in TOC content from the peat basal depth of the cores from both studied peatlands to approximately 13 cm (the early 1980s) and then the TOC values decreased to the top of the cores (2015 CE) (Supplementary Fig. 1).
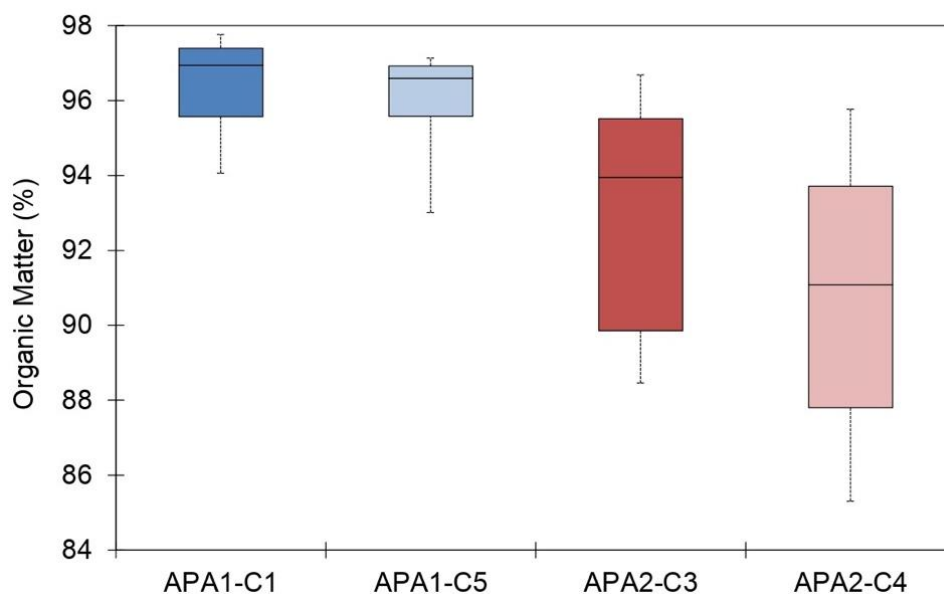
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Figure 3: Box-Plot of organic matter content (%) for the four peat cores analyzed.

CAR varied depending on age and elevation. At APA 1, mean CAR were higher that at APA 2 (Supplementary Table 1),

175 reaching a maximum of 1010 g C m^{-2} yr^{-1}, with an average of 470 g C m^{-2} yr^{-1}. The cores from APA 2, APA2-C3 and APA2-C4, had a mean CAR of 240 and 195 g C m^{-2} yr^{-1}, respectively (average: 220 g C m^{-2} yr^{-1}).

Highly variable CAR values were found from 34 to 16 cm (1971 to 1983 CE) for cores from APA 1 site (SD: 165 g C m^{-2} yr^{-1}). From 16 cm to the top of the cores, mean CAR dropped to near present values of 325 g C m^{-2} yr^{-1} (Fig. 4A). For APA 2's cores, from the peat basal depth to 14 cm (1951 to 1984 CE), average CAR diminished with a significant lower

180 variability (SD: 60 g C m^{-2} yr^{-1}) than in the peat section 34 - 16 cm from APA 1's cores. For the upper 14 cm of peat, CAR values slightly decreased to the top of the cores (mean CAR: 150 g C m^{-2} yr^{-1}) (Fig. 4B).
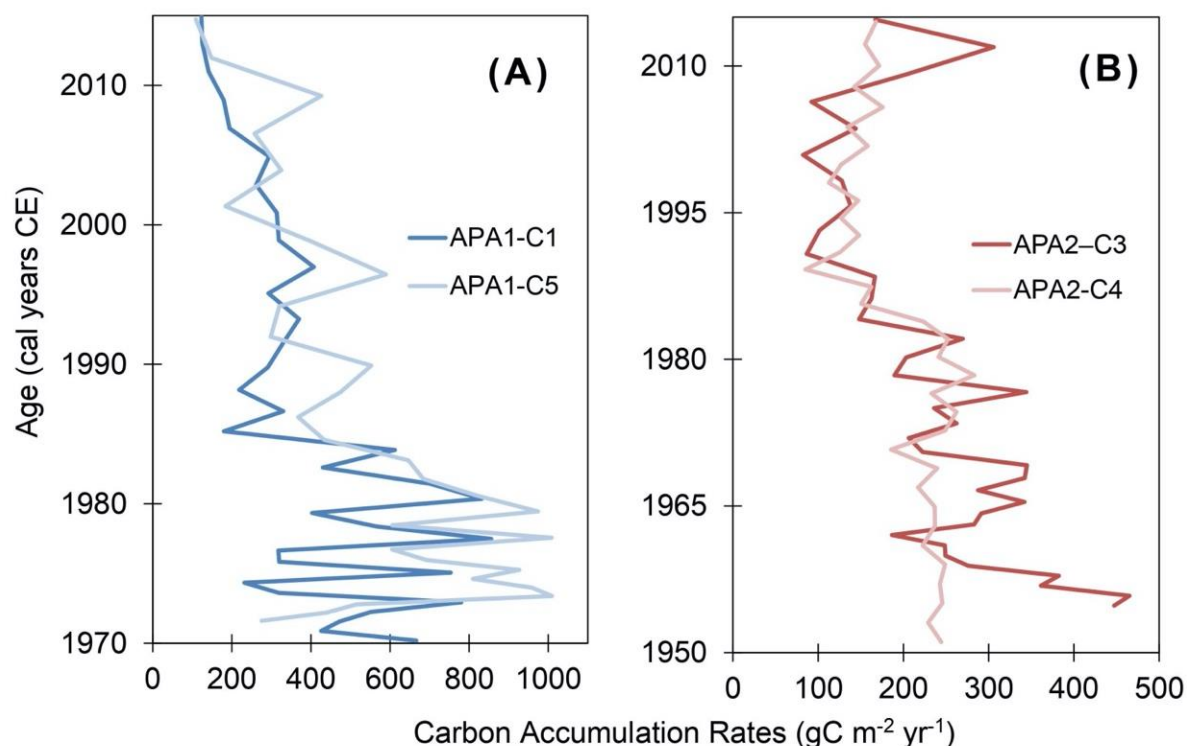
Figure 4: Carbon accumulation rates (CARs) over time in the high-Andean peatlands for the analyzed cores: (A) APA1-C1 and
185   **APA1-C5 at 4200 m a.s.l. and (B) APA2-C3 and APA2-C4 at 4420 m a.s.l.**

Stable isotopes analysis indicated δ^{13}C (Supplementary Table 1) values ranging from -27.70 to -24.44‰, consistent with C_3 plant composition for all the peat cores: mean value for APA1-C5 was -25.72‰ (SD: 1.01‰) and for APA2-C4 the average was -26.83‰ (SD: 0.60‰). At both peatlands, there was a general trend to more negative δ13C values from the basal depth
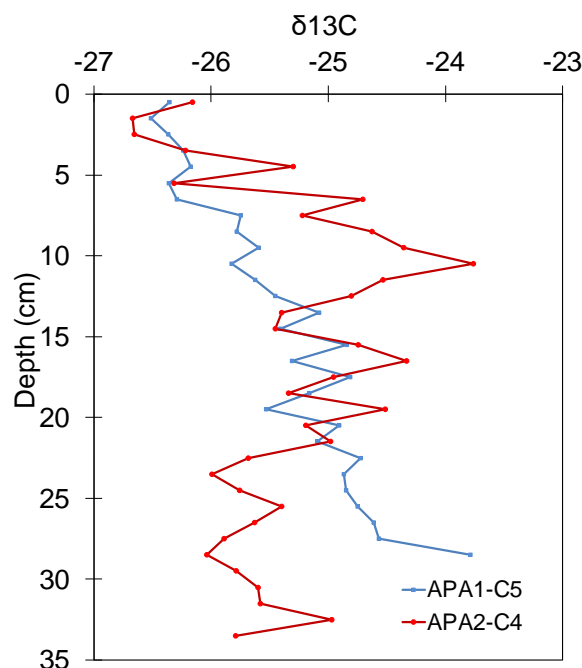190   to the top of the cores (Fig. 5).

Figure 5: Carbon stable isotope of the *Distichia* peat from the APA1-C5 and APA2-C4 cores.

5. Discussion

5.1 Carbon accumulation rates and the role of *Distichia muscoides*

Carbon accumulation rates (CAR) calculated here for the Apacheta Peruvian peatlands are among the highest when compared to other peatlands worldwide (Fig. 6). When compared to other peatlands located in the Andes, the CARs from Apacheta are notably higher than the values found in Bolivia (47 and 37 g C m^{-2} yr^{-1}; Hribljan et al., 2015) and Ecuador (46 g C m^{-2} yr^{-1}, Chimmer & Karberg, 2008; 43 and 224 g C m^{-2} yr^{-1}, Hribljan et al., 2016) with other cushion-forming dominant species: *Distichia muscoides* and *Oxycholoe andina* at the first site, and *Azorella* spp. and *Distichia muscoides* with *Plantago rigida* for the other two. On the other hand, CAR are in the same order of magnitude as those found in peatlands where *Distichia muscoides* is the dominant species in Bolivia (70 - 292 g C m^{-2} yr^{-1}, Cooper et al., 2015) and Colombia (150 - 200 g C m^{-2} yr^{-1}, Benavides et al., 2013). Our results were also higher than those recorded in peatlands in western Canada (7 - 182 g C m^{-2} yr^{-1}; Yu et al., 2003), mountains of China (9 - 129 g C m^{-2} yr^{-1}; Xing et al., 2015) and United States (95.4 g C m^{-2} yr^{-1}, Drexler et al., 2015), and also in temperate tropical peatlands (20 - 25 g C m^{-2} yr^{-1}; Cooper et al., 2010). They also are greater than rates found in tropical lowland Amazonian peatlands in Peru, where the values varied between 26 and 74 g C m^{-2} yr^{-1} for the first 175 cm of peatlands dominated by *Mauritia flexuosa* (Lähteenoja et al., 2009), and from tropical peatlands with Poaceae species in Brazil, where the rates were 151 and 243 g C m^{-2} yr^{-1} for depths of 41 and 30 cm, respectively (Lourençato et al., 2017).

210   High CAR, found in Apacheta cores, shows a scenario of slow decomposition (with high mean organic matter contents of

94%) and potentially rapid vegetal production along of all peat cores analyzed (mainly before the early 1980s), where

accumulation rates reached up to 1.7 cm yr^{-1} (Fig. 2). Consequently, during periods characterized by high accumulation

rates, CAR values were up to 1010 g C m^{-2} yr^{-1}. In our study, these great CARs can be related to the high growth rates of

Distichia muscoides, similar to previously reported values of up to 5 cm yr^{-1} in the Bolivian peatlands (Cooper et al., 2015)

215   and 3 cm yr^{-1} in Colombian peatlands (Benavides et al., 2013). Growth rates in Andean peatlands dominated by *Distichia*

muscoides are also among the highest compared to other peatlands worldwide. High rates of growth, net primary production

and C accumulation observed in Andean cushion systems dominated by *D. muscoides* are mainly the result of high rates of

insolation in the dry Andes enhancing photosynthesis, a constantly supplied groundwater table near the surface, waters with

a pH close to neutrality and high ions concentration, and finally anoxic and cold soils limiting decomposition (Squeo et al.,

220   2006; Maldonado Fonkén, 2014; Cooper et al., 2015). These plants are characterized by rapid and continuous growth

throughout the year (Cooper et al., 2015; Skrzypek et al., 2011). It has thick leaves and shoots of slow decomposition that

leads to high concentrations of organic matter. Due to typical conditions of the high-Andean peatlands (anaerobic

environment and low temperatures), their dead remains do not decompose rapidly, and the fossil tissues are deposited as a

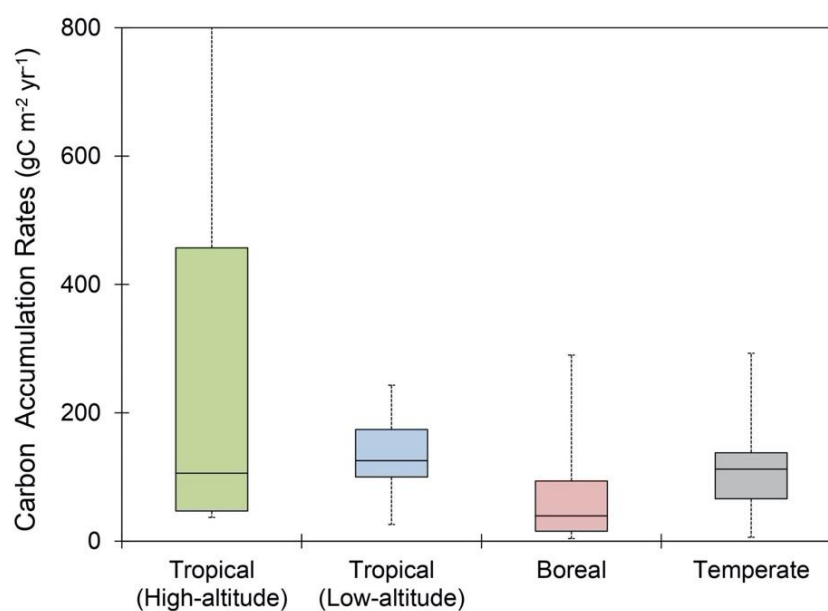peat (Schittek et al., 2015).

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Figure 6: Comparison of carbon accumulation rates (CARs) between several peatlands around the world for the top 30cm, results of this study and a compilation for: tropical high-altitude (*Chimmer and Karberg 2008, Salvador et al. 2014, Benavides et al. 2015, Cooper et al. 2015, Hribljan et al. 2015, Roa-García et al. 2016, Hribljan et al. 2016*), tropical low-altitude (*Lähteenoja et al. 2009,*
230   ***Lähteenoja et al. 2013, Lourençato et al. 2017, Hapsari et al. 2017*), boreal (*Craft and Richardson 1993, Tolonen and Turunen 1996, Turunen et al. 2001, Chimner and Cooper 2003, Turunen et al. 2004, Beilman et al. 2009, Van Bellen et al. 2011, Nakatsubo et al. 2014, Chimner et al. 2016*), temperate (*Xing et al. 2015, Bao et al. 2010*).**

Differences found in CAR (Fig. 4) from the analyzed peatlands (APA 1 and APA 2) were related to the different drainage
235   area surfaces, much larger for APA1 (130 km^2) than for APA2 (2.5 km^2) (Fig. 1) that influence the accumulation rates
(higher for APA 1 than for APA 2) (Fig. 2). Peat formation by *Distichia muscoides* and its consequent C accumulation are
also dependent on specific topographic factors, because they require topographic depressions that allow the accumulation of
few or no mineral sedimentation (Kleinebecker et al., 2010), so the visible differences between CAR from the two Andean
peatlands in this study (APA 1 and APA 2) could be also explained by their different local topography. Although there is a
240   similar downward trend in the CAR at both sites after the early 1980s, before this period we observed a greater accumulation
value for APA 1 (maximum value: 1010 g C m^{-2} yr^{-1}) than for the higher-altitude peatland (465 g C m^{-2} yr^{-1}). Therefore,
favorable topographic conditions and the larger area of its sub-catchment for APA1 (Fig. 1B) that allowed greater water
accumulation and a consequently higher water tables, which reduced the time when *Distichia* plants were exposed to aerobic
decay, ensured peat conservation and resulted in higher CAR (Glaser et al., 2004; Cooper et al., 2015; Benfield et al., 2021).

245   **5.2 Climate controls over the last 65 years and their impact on the peatlands carbon accumulation**

Climate in the tropical and subtropical Andes is changing rapidly, marked by warming, melting of glaciers and changes in
the seasonality of the precipitation, especially at higher elevations (Vuille et al., 2018). Hence regional climate changes and
the consequent glacial retreat in the Andes could represent a threat to high-altitude peatlands, because tropical glaciers are
the most important source of water to them, maintaining a steady supply and a stable water table around the year, especially
250   in *Distichia muscoides*-dominated peatlands which are typically associated with glacial dynamics (Thompson et al., 2006;
Benavides et al., 2013). The decrease of accumulation rates over the last 35 years (with values of about 0.6 and 0.4 cm yr^{-1}
for APA1 and APA2) may be related to an increase on decomposition rates due to temperature increase (Wieder, 2001;
Benavides et al., 2013).

In our study area, the temperature shows an increase during the last 65 years, most marked over the last 30 years and for
255   precipitation a marked interannual variability and a slight decrease of the total annual amount is observed over the last 65
years (Fig. 7).

So the decrease in the growth rate of peatlands after the early 1980s seems more related to temperature than precipitation.
The effect of temperature can also be indirect and linked to the retreat of glaciers. Andean peatlands are influenced by
hydrological conditions and are most abundant in areas with excess moisture (Mitsch and Gosselink, 2007; Charman et al.,
260   2008; Klein et al., 2013). It has been shown that glacial withdrawal has also an influence in the Andean wetlands area and
their connectivity (Polk et al., 2017). Changes in water balance due to variations in stream discharge dynamics related to
glacial retreat should be expected to have effects on biomass production and biogeochemical cycles (Charman et al., 2008;
Polk et al. 2017; Xia et al., 2020), and glacial melt water may feed some of the *Distichia*-dominated peatlands and buffer the
general downward trend in the precipitation observed in recent decades elsewhere in the Andes (Benavides et al., 2013). At
265   Apacheta, the glacial retreat over the last century could have fed the peatlands with melt water which would explain the high

growth rates observed before the 70s. The subsequent reduction in peat growth rates could have been due in part to the decrease in the rate of water inflow from nearby glaciers to peatlands after their complete disappearance. These expected hydrological changes would reduce water availability for cushion-plant species in peatlands (as *Distichia muscoides*), influencing their production and survival (Cooper et al., 2015) also affecting CAR by the deceleration of its rates that

270 occurred after the early 1980s for both analyzed peatlands (Fig. 4).
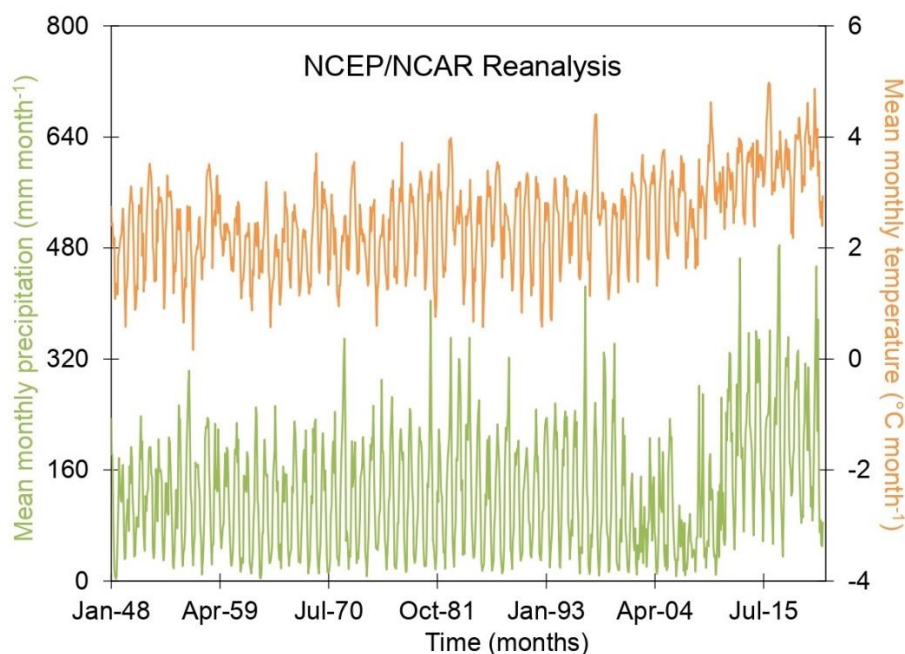
Figure 7: Monthly precipitation and temperature (at geopotential 600 mb) data over the 1948–2021 period from the NCEP/NCAR analysis.

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Our results highlight the clear decrease of the $\delta^{13}C$ from the bottom towards the top of all cores (Fig. 5). It has been shown that changes in mean air temperature have a direct effect on the composition of C stable isotope ($\delta^{13}C$) of *Distichia* peat (Skrzypek et al., 2011; Engel et al., 2014). Very strong gradients in $\delta^{13}C$ with elevation, on the order of 0.4‰ per 100m, have been observed in Andean *Distichia* as well as in surface peat (Skrzypek et al., 2011). Part of this gradient may be due

280 to the decrease in atmospheric pCO_2 with altitude, but observations and theoretical calculations conducted in the Alpes show that this effect is small, less than 0.08 ‰/100m (Menot and Burns, 2001). Furthermore, according to these authors, vascular plants can adapt to CO_2 variations by changing their photosynthetic rate and stomatal conductance (leaf size, stomatal opening, stomatal density, etc.) which minimizes the effects of atmospheric pCO_2 variations. The strong gradients in $\delta^{13}C$ with elevation measured on Peruvian peatland *Distichias* are therefore interpreted as being primarily due to the temperature

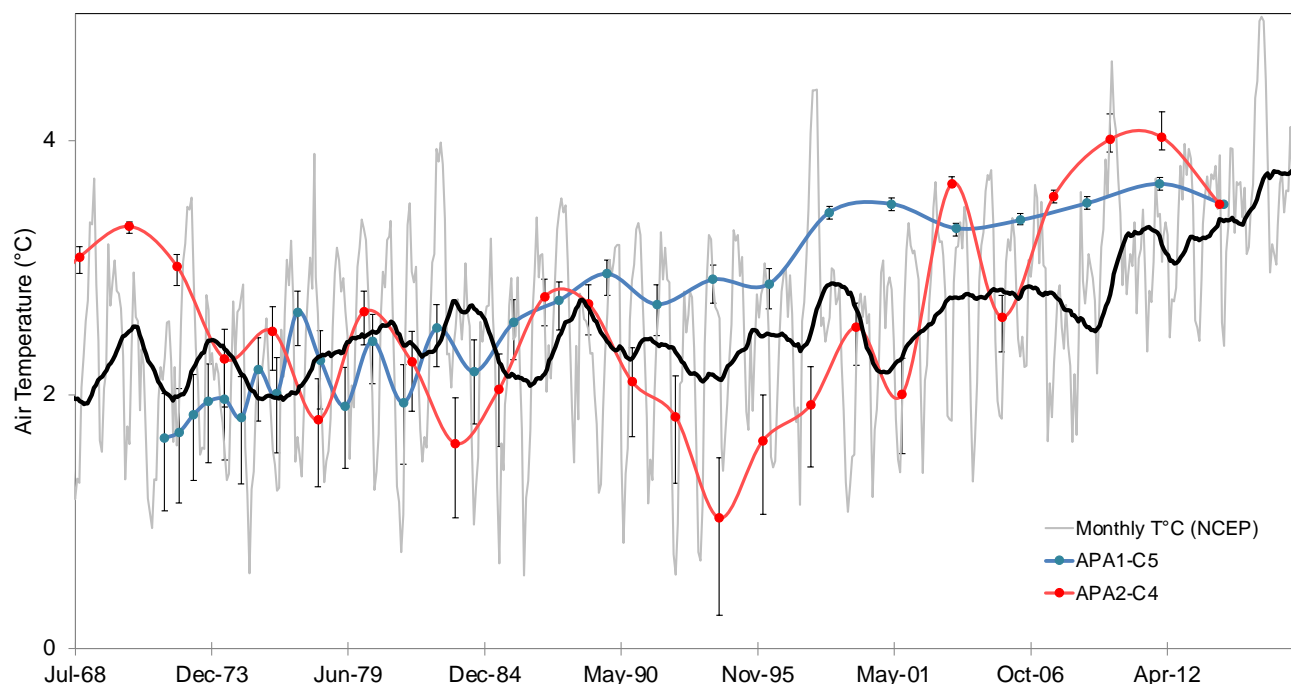285 gradient and the impact of temperature on photosynthetic responses (Skrzypek et al., 2011).

Figure 8: Monthly temperature from NCEP/NCAR analysis and two-year moving average (black line), reconstructed temperature using δ ^{13}C data from the two core samples APA1-C5 and APA2-C4.

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The comparison made using the δ^{13}C data to reconstruct the temperature in the study area and the NCEP temperature data showed a good relationship especially in trends. This confirms the use of this proxy for recent temperature reconstruction studies (Fig. 8). Of course, this comparison is difficult because the NCEP data are reanalysis data that may differ from the peatland temperatures themselves and because we do not know precisely what time period each peat sample corresponds to.

295 The NCEP data reanalysis, show a temperature increase average at the site of 2.15 °C for the last 45 years and we observed a general trend of increase in the reconstructed temperature from both studied peatlands from 1.9 to 2 °C for the same period (1970–2015 CE).

The temperature increases and the decrease in CAR in the Peruvian Andes strongly suggest an increase in the rate of decomposition of organic matter. Recent results propose that microbial activity in peatlands increases with rising

300 temperature, thus increasing decomposition (Bell et al., 2018; Galego-Sala et al., 2018). In this sense, temperature increase seems to be an unfavorable conservation condition for *Distichia muscoides* cushion plant-dominated Andean peatlands. Air temperature in tropical Andes is increasing fast, and massive warming of 4.5 to 5.0 °C is projected by the end of the 21st century under the IPCC A2 scenario (high emission) (Vuille et al., 2008), with a considerably rise not only in the temperature but in their interannual variability (Urrutia and Vuille, 2009). Because the climate is changing rapidly, there is

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305 an increasing need to understand how water and soil resources respond to climate change and what will be its consequences on the stability and distribution of the Andean ecosystems.

6. Conclusion

Distichia muscoides-dominated peatlands represent a significant C reservoir and consequently play an important role in the regional (and even global) C cycle, despite their small surface. This highlights the role of these peatlands as C sinks that
310 contribute to the mitigation of global climate change. The CARs measured in this study are among the highest in the world. Rapid growth, slow decomposition and high accumulation rates are mainly responsible for the high CAR found in Andean peatlands over the last 65 years. Although this system still represents one of the most or the most important C reservoirs of the Andes, a clear decrease of this accumulation has been observed since the end of the 1970s.

This decline in C accumulation was mainly related to the temperature rise which increases the organic matter degradation
315 rate. Another effect of the temperature increase is the glacier retreat that potentially has fed with melting water and nutrients the peatlands inducing very high CAR. The decline of these inputs and the almost total disappearance of glaciers has probably contributed to the decrease of CAR in the last decades.

Our findings highlight that tropical Andean peatland seem to be one the most vulnerable ecosystem face to climate change. The relation between climate conditions and C accumulation suggests that future changes in the environment (such as
320 increasing temperatures, decreasing water inputs and glacial disappearance) may threaten the continuity of peatlands, especially in the high-mountain Andes, resulting in an uncertain future for these peatlands, which could perhaps go from being C stores to emitters. With the decline of peatlands, an important compartment of water storage in the Andes is also disappearing.

325 **Data availability**

The data associated with this manuscript will be submitted in the IRD database upon publication of this paper.

Author contributions

P.M.T with contribution of B.T. and B.W. designed the study project. Y.H. and R.E.V. planned fieldwork and collected
330 samples. R.L. analyzed the samples and processed the data. T.C. contributed to critical analysis of climatic data. R.L., P.M.T. and B.T. wrote the manuscript. All authors provided critical feedback and helped the final manuscript.

Competing interests

The authors declare that they have any competing interests.

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