RECONSTRUCTION OF PAST ENVIRONMENTAL CHANGES IN SOUTHERN PATAGONIA USING STABLE ISOTOPES

An Undergraduate Research Scholars Thesis

by
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Submitted to the Undergraduate Research Scholars program at
Texas A&M University
in partial fulfillment of the requirements for the designation as an

UNDERGRADUATE RESEARCH SCHOLAR

Approved by Research Advisor: Dr. Julie Loisel

May 2020

Major: Environmental Studies

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ABSTRACT

Reconstruction of Past Environmental Changes in Southern Patagonia Using Stable Isotopes

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Paleoclimate reconstructions allow us to build a better picture of how climate has changed over time. However, relatively little research has been done in the higher latitudes of the southern hemisphere, leaving a gap in our knowledge. Changes in temperature and moisture can have significant impacts on local vegetation growth structure and ecosystem functioning; these changes in hydroclimatic conditions can be traced using stable isotope analysis of carbon ($\delta^{13}C$), oxygen ($\delta^{18}O$), and hydrogen ($\delta^{2}H$) in peat deposits. Throughout this project, I aimed to determine the effects of changes in precipitation amounts and sources of moisture in southernmost Patagonia using peat-core samples collected in 2010. The top 350 cm (~ 4200 cal. BP) of the core was analyzed in 2-centimeter increments. For each horizon, *Sphagnum magellanicum* moss stems were handpicked and cleaned. Cellulose from the moss stems was then extracted following the alkaline bleaching method and the samples were analyzed for $\delta^{13}C$ and $\delta^{18}O$ using a mass spectrometer. The combination of these isotopes allows to tease apart local (soil moisture) vs. regional (moisture source) environmental effects. On the basis of previous studies, cellulose values that are more depleted in the heavier isotope are expected to

correspond to wetter conditions (and less depleted values with drier conditions). Our results show a progressive wetting of the peatland from 4000 years ago until approximately 1500 years ago; conversely, the past 1000 years have seen drying conditions. These results coincide with other regional paleoclimate reconstructions that suggest decreased winds during the earlier period (which can be interpreted as wetter conditions, likely due to lower evaporation), and vice versa during the more recent period.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Julie Loisel, for all her guidance throughout this project, both the research and writing of this paper. Without her help, this project would not have been possible. I would also like to express my gratitude Dr. Chris Maupin for his help and the use of his lab for the testing with the mass spectrometer. In addition, I am very appreciative of all the undergraduates who helped to clean and bleach all the stem samples for analysis at the beginning of this project.

SECTION I

INTRODUCTION

Paleoclimatic reconstruction is a crucial part of understanding past climate and how it has changed over time. This analysis guides our understanding of regional climate and important climatic changes over the relatively recent history of Earth. Weather often operates in distinguishable patterns with intermittent anomalies. Paleoclimate reconstruction allows us to create a better understanding of not only what climate was like but also how it may change in the future. Isotopes found within natural archives (e.g., ice cores, peat cores, ocean and lake cores, tree rings) reveal the way important climatic factors, such as regional wind and rain patterns, have shifted in the past.

Southern Patagonia (~ 45-55°S) is located in the middle of the Southern Hemisphere. The research done on past climate in the Southern Hemisphere has been very limited due to the limited land area, relatively few natural past climate archives, and poor access to many areas. Centennial shifts in temperature and precipitation in the Northern Hemisphere have been linked to the Medieval Warm Period and the Little Ice Age (Moreno et al., 2014). However, because of the paucity of Southern Hemisphere research, the understanding of the centennial shifts in that region is much less complete. The southern hemisphere climate system plays a key role in the global atmospheric circulation, and a better understanding of its past and present dynamics are important to better assess its impacts on equatorial and northern climate change.

The weather and climate in southern Patagonia are affected dramatically by the Southern Westerly Winds (SWW) and also less dramatically by the Southern Annual Mode (SAM). The SWW is responsible for bringing moisture from the Pacific Ocean to the continent. The forcing of winds over and against the Andes mountain range leads to a strong precipitation gradient from west-to-east, with annual precipitation well over 4000mm per year on the West side vs. arid steppe conditions (< 100mm per year) on the East side (Moreno et al., 2018). Southern Patagonia is the only continental landmass that is located in the middle of the SWW. This makes Patagonia an important and unique historical record. As the westerlies shift to the North and to the South over centennial and millennial timescales, they can have dramatic impacts on the weather of regions in Patagonia (Garreaud, 2007). Superimposed on these changes is the SAM. During the positive phase of the SAM, the westerlies move towards the poles resulting in weaker winds for at the mid-latitudes. In a negative SAM phase, the opposite occurs, the westerlies move in a equatorial direction weakening the winds at the poles. The impacts of the El Niño-Southern Oscillation (ENSO) on the SAM can also affect temperature and precipitation greatly (Wang and Cai, 2013). The warm sea surface temperatures that drive ENSO create atmospheric waves that move poleward resulting in a negative polarity of SAM (Moreno et al., 2018). The opposite occurs during a La Niña phase of ENSO. ENSO variability can increase the cycling of SAM and strengthen the conditions it brings. Because there is very little landmass in the Southern Hemisphere, reconstructing climate in Patagonia can build a better picture of how the SWW and SAM (and its association with ENSO) have changed over time in a way that cannot be seen in any other records.

In this thesis, I am using a peat core to reconstruct changes in past climate. Peatlands are important natural archives of climate, especially in southern Patagonia, where they are abundant. Peatlands are incredibly important carbon sinks. In peatlands, vegetation grows on the surface of other layers of vegetation. This results in the moss becoming submerged where it breaks down into a carbon rich soil called peat. Peatlands are estimated to store up to one fifth of global carbon (Köchy et al., 2015). Another key characteristic of Patagonian peatlands is that a large number of them are ombrotrophic, i.e., they entirely derive their moisture and nutrients from the atmosphere, making them particularly sensitive to changes in atmospheric conditions without influences from the groundwater systems. In addition, many of these peatlands are dominated by *Sphagnum* peat moss, a type of bryophyte that lacks roots and stomata, such that it is at the mercy of changing atmospheric conditions. The consistency of *Sphagnum* throughout the length of the core provides the opportunity to study a comprehensive record of climatic shifts that are stored in the isotopic values of the *Sphagnum* plants. In addition to their role as climate archives, peatlands also play a key role in sequestering and storing carbon (Gorham, 1991).

Peat-based paleoclimate reconstructions allow us to build a better picture of how climate has changed over time. Changes in temperature and moisture can have significant impacts on local vegetation community structure and peatland ecosystem functioning. For example, prolonged droughts lead to low soil moisture content, intensified peat decomposition, and potentially changes in peatland vegetation. At the decadal scale, such changes in hydroclimatic conditions can be traced in peat deposits using stable isotope analysis of carbon ($\delta^{13}C$), oxygen ($\delta^{18}O$), and hydrogen ($\delta^{2}H$). Changes in circulation, both in the atmosphere and the ocean, can largely alter vegetation growth (Paruelo et al., 1998). These alterations are stored within the peat record and thus the analysis of the isotopes within the core can help us build a picture of how wind patterns, which largely influence precipitation and temperature regimes, have changed within a region.

In my research, I am using $\delta^{13}C$ to reconstruct changes in the hydrology of a peatland (Loisel et al., 2009). As mentioned above, *Sphagnum* is extremely responsive to climatic shifts and thus provides a good proxy for climate. In plants, the carbon isotopic ratio is determined by the isotopic composition of the carbon source, which is carbon dioxide from the atmosphere. *Sphagnum* are non-vascular plants and thus, do not regulate their uptake of carbon dioxide because they lack stomata. As CO_2 diffuses into the plant, it is influenced by the wetness of the *Sphagnum* membrane. When *Sphagnum* tissues are wet or flooded, the thick water film around the photosynthetic cells makes it harder for CO2 to diffuse to the plant. As a response, *Sphagnum* is less 'picky' about which carbon isotope to use (^{12}C or ^{13}C) (Farquhar et al., 1989). Conversely, under dry conditions, CO_2 diffusion is much easier, than *Sphagnum* preferentially uptakes ^{12}C because of its lighter weight and easier assimilation for photosynthesis (Price et al., 1997). Because of this diffusion process, the mosses' isotopic values are thus highly sensitive to changes in the physical environment that impact the carbon dioxide (and resulting carbon) that is diffusing into the plant. Changes between wet and dry conditions impact the stable carbon isotope fractionation within the moss (Moschen et al. 2008). Through examining the $\delta^{13}C$ values, we can determine the climatic conditions at the time of the plant growth, a thick water film leads to less negative $\delta^{13}C$ values, and vice versa (Loisel et al. 2008). This means that the $\delta^{13}C$ can be used to reconstruct not only climactic changes but also the conditions at the growth of the specific *Sphagnum* sample from the core.

SECTION II

METHODS

Study Site and Field Methods

2.1 Study Site and Field Methods

The core that I used for this study was collected in January 2010 from Cerro Negro peatland in Southern Patagonia, Chile (Figure 1; 52.07°S, 72.03°W, 217 m a.m.s.l.). Cerro Negro is located on the lee side of the Andes, about 150 km north of Punta Arenas and 100 km south of Torres del Paine National Park (Loisel and Yu, 2013). This region is relatively dry with mean annual precipitation in Punta Arenas of 376 mm, mean January temperature of 10.6 °C, mean July temperature of 1.3 °C, and mean annual temperature of 6.3 °C (Dirección Meteorológica de Chile, 2012). Cerro Negro is a peatland complex that consists of two raised bogs dominated by *Sphagnum magellanicum* and characterized by hummock-hollow microtopography; our peat core (445 cm-long) was collected in the highest but smallest (about 0.7 km^2 in area) of these raised bogs. Note that the Cerro Negro peatland is located approximately 12 km west of the Rio Rubens peatland (Figure 2) that was studied by Huber and Markgraf (2003) and Huber et al. (2004). Due to the marked longitudinal precipitation gradient across this region, the Cerro Negro and Rio Rubens sites have markedly different records of past climates.

The PAT-CN2010 peat core was collected in 50-cm increments using a Russian-type corer. To minimize compaction of the acrotelm (surface layers), a box corer was used to retrieve the top meter of peat. The collected cores were wrapped in plastic film, secured in PVC pipes, transported to the laboratory, and stored at 4°C until analysis.

In addition, 30 *Sphagnum magellanicum* surface samples were collected across a total of 5 Patagonian peat bogs (Figures 1a and 1b). Those samples were approximately 10 x 10 x 10 cm in size. They were hand-picked in the field at different heights above the water table to generate a transfer function between water table depth (WTD), moss water content, and the carbon isotopic signature of *Sphagnum magellanicum*. Each sample was weighted on site, stored in a plastic bag, and kept at 4°C until analysis.

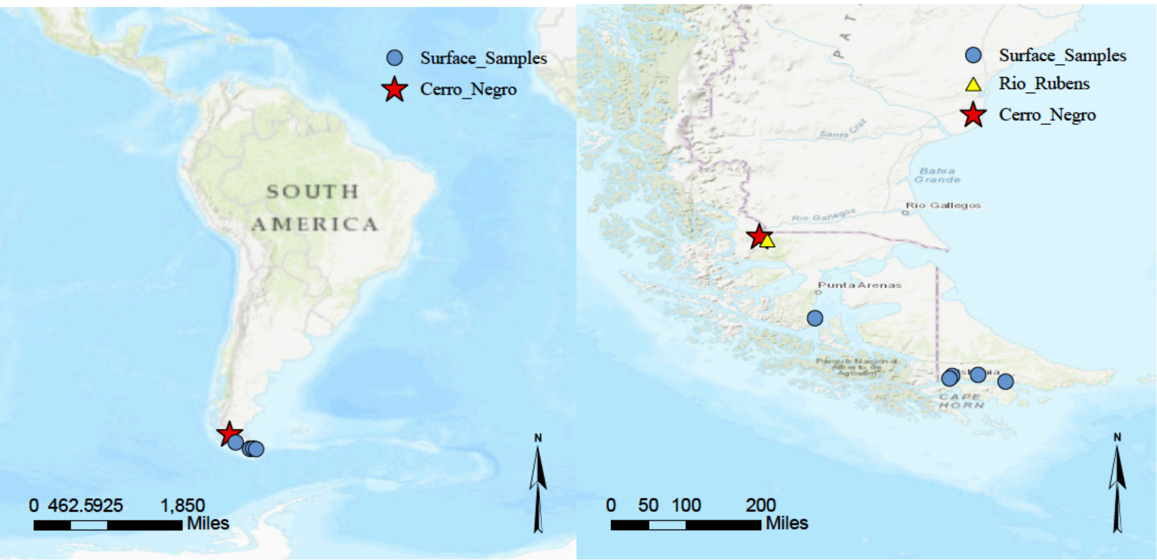

Figure 1a (left) and 1b (right). Maps created using ArcGISPro depicting the location of the surface sample and Cerro Negro core sites as well as the Rio Rubens core site.

2.2 Age-Depth Model

Peat core chronology was established using AMS radiocarbon (^{14}C) dating method (Table 1). A total of 18 ^{14}C dates were used to constrain the chronology of core Cerro Negro. Dating material was hand-picked and cleaned with distilled water and was exclusively composed of non-aquatic plant macrofossil remains (e.g., *Sphagnum* stems and leaves, seeds, sedge stem bases). In horizons that lacked plant macrofossil dating material, root-free bulk peat samples were analyzed. The ^{14}C samples were submitted to Keck AMS Carbon Cycle Lab at University of California, Irvine. Results were calibrated using the program Bacon, a flexible Bayesian age-depth modeling approach (Blaauw and Christen, 2011) that was used in conjunction with the INTCAL09 calibration data set (Reimer et al., 2009). Post-modern ^{14}C dates were calibrated using CALIBomb and a concatenation of the Levin's Vermunt and Schauinsland calibration datasets (Levin and Kromer, 2004).

2.3 Laboratory Analysis

2.3.1 Plant macrofossil analysis

Plant macrofossil analysis was carried out at every centimeter along the CN core (from 0 to 445 cm) following standard procedures (Mauquoy and van Geel, 2007; Loisel and Yu 2013). Peat sub-samples (2 cm^3) were gently boiled and rinsed with distilled water through a 150-μm sieve. For each sample, Sphagnaceae, Amblystegiaceae, herbaceous, ligneous and unidentifiable organic matter (UOM) material were quantified as a percentage of the total sample by volume.

2.3.2. Stable isotopes (d^{13}C) of *Sphagnum* cellulose

Sphagnum magellanicum moss stems were washed with distilled water at 2cm increments along the Cerro Negro core. A dissecting microscope was used to clean the stems and pluck off individual leaves. For every increment, the goal was to collect and clean at least fifteen stems. Samples that did not reach the target weight were marked as having too small of an amplification during analysis. Cellulose from these moss stems was then extracted following the alkaline bleaching method (Loader et al. 1997). This method involves soaking the stems five times in sodium chlorite acid for increments of fifty minutes. Then the stems were washed in distilled water and soaked in sodium hydroxide for forty-five minutes. Then (if necessary), the stems were washed with distilled water and soaked in sodium chlorite acid again twice. The cellulose samples were then homogenized using a sonifying probe to break the cellulose up; the samples were kept in vials of distilled water and frozen, then freeze-dried prior to analysis. Note that the surface samples underwent an identical treatment.

The cellulose samples were weighed on a microbalance into tin capsules. The target weight for the carbon samples was between 0.5 and 0.6 mg. The weighed samples were analyzed for $\delta^{13}C$ at the Texas A&M Stable Isotope Geosciences Facility using a Thermo Scientific Flash EA Isolink Elemental Analyzer attached to a Thermo Scientific Conflo IV and a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer (IRMS). This equipment identifies isotopic compounds using gas chromatography prior to quantifying isotopic composition using combustion (with pure O_2 at $1020^{o}C$) in combination with mass spectrometry. Stable isotope values are reported in parts per thousand, or per mil (‰), as a ratio of the abundance of the heavy to the light isotope. For carbon, the ratio is $^{13}C/^{12}C$, respectively. $\delta^{13}C$ in the samples are measured relative to their abundance in an international standard (V-PDB calcite standard) and described in terms of depletion or enrichment of the heavy isotope (Sharp 2007).

SECTION III

RESULTS

3.1 Cerro Negro Chronology

Peat inception occurred approximately 9000 calibrated years ago (cal. BP). The peat accumulation profile is characterized by a generally convex curve, with a slow rate of peat accumulation until approximately 4200 cal. BP that is followed by a rapid increase up until the present (Figure 3). This change in peat accumulation rate coincides with a sudden shift in vegetation, from herbaceous peat prior to 4200 cal. BP to *Sphagnum* peat since then.

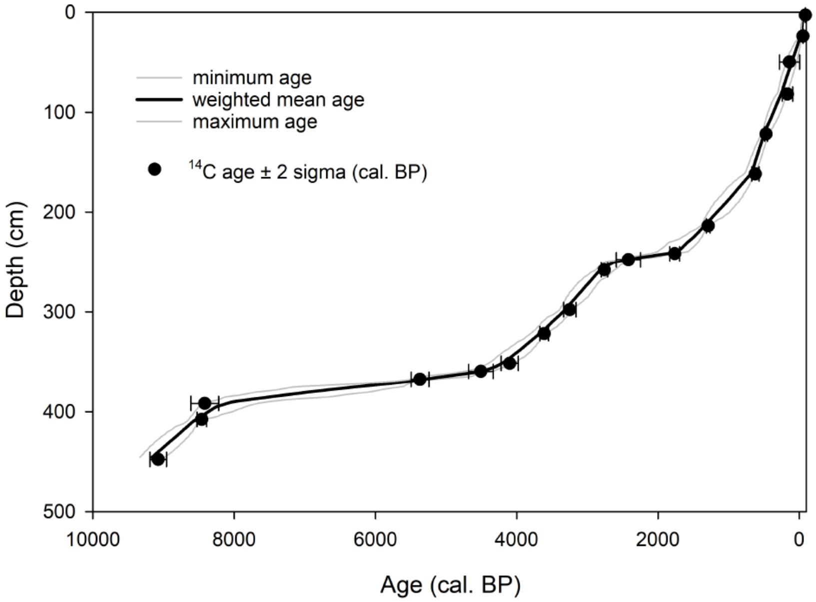

Figure 3. Age-Depth model created using data from the Cerro Negro core.

3.2 δ^{13}C analysis and plant macrofossils

The results from the δ^{13}C measurements show a trend with the values becoming more positive until around 1500 cal. BP where the values begin to move in the more negative direction (figure 4). There are two noticeable peaks in the data around 1500 and 800 cal. BP as well as smaller peaks around 3300 and 3800 cal. BP. The *Sphagnum magellanicum* (%) was based on the plant macrofossil analysis and shows more small-scale variations. In general, this curve shows centennial-scale shifts between wet and dry plant assemblages from 4200 cal. BP until today. From 4200 to 2800, the cycles are closer together (~150-year cycles), suggesting high precipitation variability (possibly due to the intensification of the westerlies). The period of these cycles then slows down during the late-Holocene but reaccelerates 100 years ago. The relationship between *Sphagnum magellanicum* (%) and $\delta^{13}C$ appears to be inversely related, with high *Sphagnum magellanicum* percentages corresponding to more negative $\delta^{13}C$ values. This is expected, because these conditions both indicate drier conditions at the peatland surface. The other curves were calculated on the basis of preliminary geochemical measurements that were performed along the core before I joined the research team. Peat-carbon accumulation rates (PCAR) show three general trends: (1) higher-than-average carbon accumulation from 4200 to 2800 and 1500 to 800 cal. BP; these time periods coincide with high *Sphagnum* percentages; (2) lower-than-average carbon accumulation from 2800 to 1500 cal. BP; this period corresponds to the low *Sphagnum* percentages; (3) very high carbon accumulation over the past 500 years associated to the incomplete decomposition of young peat. The peat density graph tracks changes in the level of compaction of the peat matrix and was used to calculate PCAR. Lastly, the organic matter content allows to identify non-peat layers within the core stratigraphy. The low peaks correspond to volcanic ash layers (tephras) that were deposited during the peatland development.

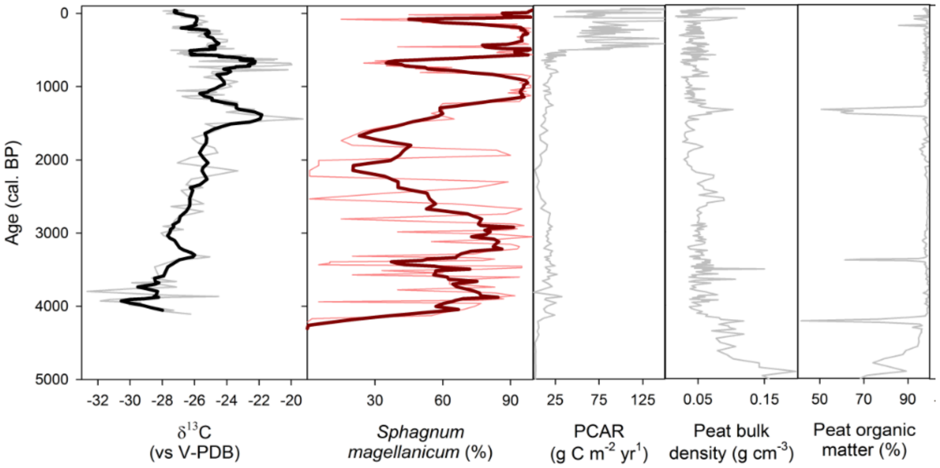

Figure 4. *Sphagnum magellanicum* (%) and δ^{13}C data from the core used for this study.

3.3 Surface samples

Data from our lab establish the relationship between water table depth, water content of the *Sphagnum*, and ultimately the δ^{13}C of the moss stems (Figures 5-7). When there is lower moss water content (a smaller percentage of dry mass) and lower water table depth (more centimeters below the surface), there is also an observed more negative Sphagnum δ^{13}C; this relationship underpins my interpretation of the downcore δ^{13}C results (see below).

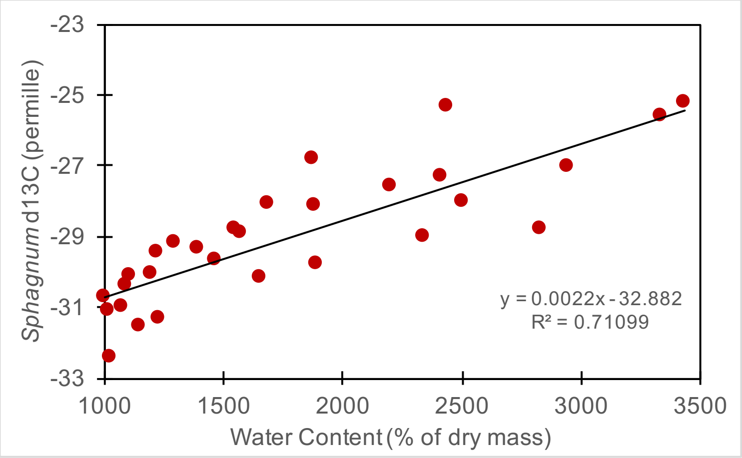

Figure 5. Unpublished data from our lab depicting the relationship between water content and Sphagnum d13C.

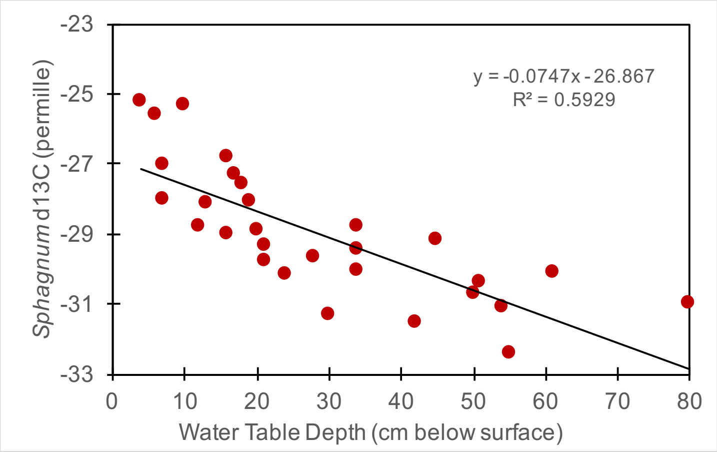

Figure 6. Unpublished data from our lab depicting the relationship between water table depth and Sphagnum d13C.

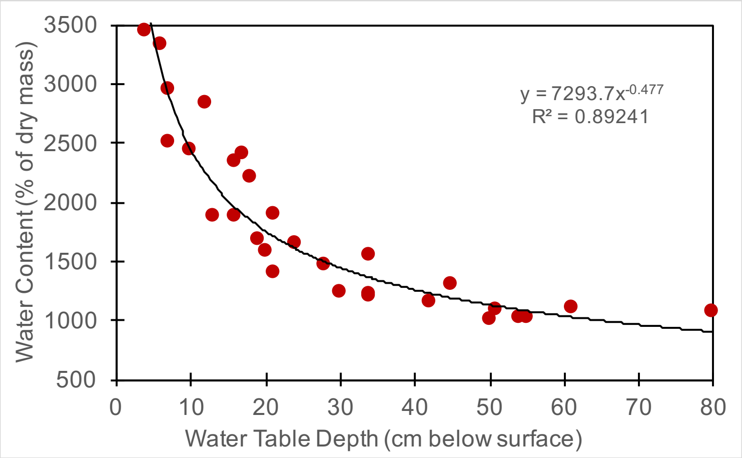

Figure 7. Unpublished data from our lab depicting the relationship between water table depth and water content.

SECTION IV

CONCLUSION

In order to determine if the changes seen along my core from Cerro Negro are merely local changes, my records were compared the records from Lago Cipreses, a site located in a nearby region (figure 8). The red and blue horizontal rectangles represent Cipreses Cycles (CC) during the period. These are alternating patterns of dry/warm (red) and cold/humid (blue) phases according to Moreno et al.'s (2018) paper. From this comparison, there seems to be peaks in the $\delta^{13}C$ values of the Cerro Negro record (3rd panel) around similar time periods to peaks in the pollen percentage at Lago Cipreses. Based on my hypothesis, these peaks would represent changes in climate leading to wetter conditions. The similarities between the records (as shown by the yellow, green, blue, and red circles) make it likely that climatic shifts are driving the changing patterns of wetting and drying as opposed to being attributable to local, isolated changes in the vegetation of the peatland.

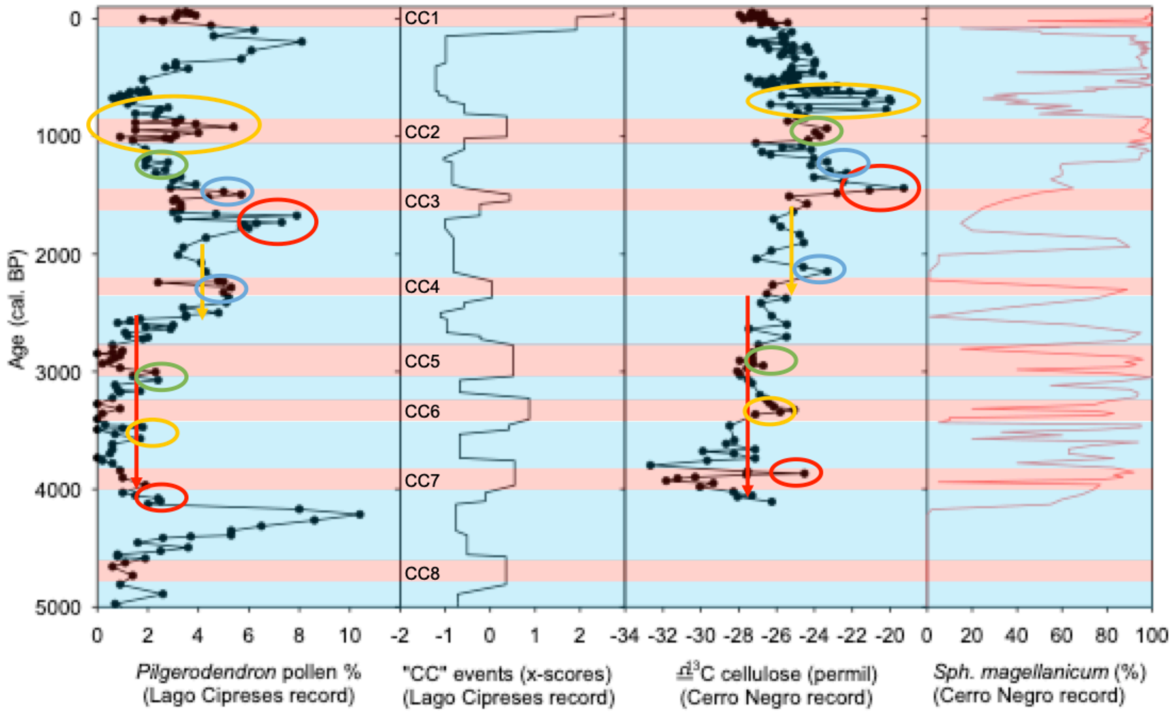

Figure 8. A comparison of the records from Cerro Negro and Lago Cipreses (data from Moreno et al., 2018).

Overall, the paleoclimatic records of the SWW are still relatively limited due to the limited research and land area in the Southern Hemisphere. However, our record from Southern Patagonia could point to shifts in the patterns of the SWW resulting in different moisture conditions in the peatland. There is a cycling effect that can be observed in our record as well as the record from Lago Cipreses due to the centennial time-scale of the westerlies.

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