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Modulation of Fire Regimes by Vegetation and Site Type in Southwestern Patagonia Since 13 ka

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The degree to which vegetation and site type have influenced fire regimes through the Holocene has not been investigated in detail in the temperate ecosystems of southern Patagonia. Here we present a first attempt using a paired-basin approach to study the evolution of fire regimes in sectors dominated by humid *Nothofagus* forests and the xeric Patagonian steppe in the Magallanes region of Chilean Patagonia (51°S). We analyzed sediment cores from two small lakes and a bog located within the same climate zone on opposite sides of the forest-steppe ecotone, ~28 km apart. The position of this biological boundary east of the Andes is controlled by the strength and position of the southern westerly winds, which constitute the sole source of precipitation throughout western Patagonia. Our results indicate that fires have occurred in the study region repeated times over the last ~13,000 years at bi- and tridecadal timescales. Sectors currently dominated by Patagonian steppe feature high frequency and low magnitude of local fires, and vice versa in humid forests. Climate-driven expansion of *Nothofagus* scrubland/woodland into steppe environments over the last ~4,200 years increased the magnitude and lowered the frequency of fire events, culminating with peak *Nothofagus* abundance, fire magnitude and frequency during the last millennium. We also detect divergences between lake-based vs. bog-based paleofire histories among paired sites located within the Patagonian steppe, ~12 km apart, which we attribute to local burning of the bog at times of lowered water table. This divergence suggests to us that bog-based vegetation and fire histories exacerbate a local, azonal, signal blurring extra-local or regional regimes, thus accounting for some discrepancies in the Quaternary paleovegetation/paleoclimate literature of southern Patagonia.

Keywords: fire regime, vegetation dynamics, paleoclimate, Patagonia, lake sediments

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INTRODUCTION

Fire regimes have shaped the structure, composition and functioning of nearly all terrestrial ecosystems at global scale, affecting sedimentary and geomorphic processes (Kean et al., 2011), atmospheric chemistry (Galanter et al., 2000), radiative balance (Zhang and Wang, 2011), and the global carbon cycle (Van Der Werf et al., 2004). Fire regimes have changed in the past in response to shifts in mean climate state and variability, vegetation type, land-use changes, and are expected to change during the twenty first century as a consequence of climate change and anthropogenic pressure on the landscapes (Krawchuk et al., 2009). Hence, it becomes a necessity to improve our understanding of the linkages between climate, vegetation type, fire regimes, and human perturbations to predict the potential consequences of future climate change, and for increasing societal preparedness and resilience.

Global-scale studies have postulated that wildfires in forest ecosystems are limited by the desiccation of fuels during warm/dry intervals, considering that abundant and spatially/temporally continuous biomass is available for burning (Krawchuk et al., 2009). This concept, known as the varying constraint hypothesis, also states that wildfire occurrence in drier landscapes dominated by grasslands and sparse scrublands is constrained by the amount and continuity of fine fuels rather than the occurrence of warm/dry intervals. Syntheses and analyses of biomass burning at global scale over the last 21,000 years have revealed a monotonic increase in fires with temperature given intermediate moisture levels (Daniau et al., 2012). These large-scale spatial and temporal patterns can be tested at the landscape level and multidecadal time scales using detailed fire histories from contrasting physiognomic units, ideally from the same region and subject to the same climatic forcing.

Fire histories extending beyond instrumental records or historical accounts have been developed with high temporal and spatial precision using fire-scar chronologies from tree rings and, with lower precision but larger time spans, from stratigraphic records. Charcoal particles and organic compounds released during combustion are preserved in multiple settings across the landscape, including soils, lake sediments, wetland and aeolian deposits, glaciers, etc. Sedimentary records from small closed-basin lakes offer the opportunity to develop continuous time series of past vegetation, charcoal particles as a proxy for paleofire, and environmental change at relatively small spatial (a few km^2) and temporal scales (decadal to millennial). This allows exploring the modulation of fire regimes by vegetation type through time, space and climatic states.

Southern South America is an interesting region to explore the linkages between climate, vegetation and fire regimes, and their likely evolution under future climate scenarios. Large-scale fires in recent years highlight the vulnerability of natural and managed landscapes to a widespread (and ongoing) megadrought (Garreaud et al., 2017). Lightning strikes, Native American burning and volcanism provide likely sources of ignition in pre-European time throughout the region, the geographic and stratigraphic dimension of which is unconstrained or partially constrained by available data. Regional vegetation and fire syntheses in this region have relied primarily on records retrieved from bogs (Huber et al., 2004; Whitlock et al., 2007; Power et al., 2008), many of which exhibit limited stratigraphic and chronologic control, non-contiguous sampling and coarse temporal resolution. A broad-scale synthesis of fire patterns between 34°and 54°S (Whitlock et al., 2007) identified widespread enhancement of fire activity between 12 and 9.5 ka (ka = 1,000 calendar years before 1950 CE), a generalized decline and spatial heterogeneity between 9.5 and 6 ka, and intensification of that variability during the last 3,000 years. These results were interpreted as multi-millennial changes in the Southern Westerly Winds (SWW), a pattern that Fletcher and Moreno (2012) subsequently interpreted as a zonally symmetric decline in SWW strength in the southern mid-latitudes. A global synthesis and analysis of charcoal records by Power et al. (2008) produced regional paleofire curves through standardization, transformation and rescaling of individual site data. The South American summary curve is fully compatible with the patterns identified by Whitlock et al. (2007) and indicates positive anomalies in fire activity during the early Holocene, a subsequent decline and negative anomalies during the mid-Holocene, and renewed fire activity over the last ∼4,000 years. One complication in those records, however, is that terrestrial vegetation growing on the bog surfaces may impose a biased palynological and paleofire history, blurring the interpretation of extra-local and regional vegetation, fire-regimes and climate change.

In this paper we examine the impact of vegetation type on local fire regimes at multidecadal scale and fine spatial resolution during the last ∼13,000 years using, for the first time, continuous pollen and macroscopic charcoal records from two lakes and a bog located in mixed evergreen-deciduous *Nothofagus* forests and the xeric steppe in southwestern Patagonia. These data allow testing the applicability of the varying constraint hypothesis to vegetation and fire-regime changes from multidecadal to millennial timescales during the Holocene.

STUDY AREA

Southwestern Patagonia (50–55°S) is a key region in the southern middle latitudes for deciphering the evolution of the SWW and their impact on terrestrial ecosystems during and since the last glaciation. The SWW supply abundant precipitation on the windward side of the Andes, as moisture-laden air masses are forced to ascend the cordillera causing copious orographic rains. The descent and acceleration of moisture-deprived air masses causes a rain shadow effect east of the Andes, which accentuates farther east in the extra-Andean plains. The interplay between the SWW and the Andes cordillera generates a vast diversity of environments along west-to-east, north-to-south and altitudinal axes, and from sea level to the high Andes, influencing the structure and composition of the land biota, as well as the frequency and magnitude of disturbance regimes, including fire. A west-to-east transect across the Andes at latitude 51°S (Villa-Martínez and Moreno, 2007) shows Magellanic Moorland communities along the windswept hyperhumid sectors adjacent to the Pacific coast, this unit is replaced by Evergreen Magellanic forests dominated by *Nothofagus betuloides* further east, Deciduous forests dominated by *N. pumilio* and *N. antarctica*, and Patagonian Steppe east of the Andes. This zonation reflects an eastward decline in precipitation of westerly origin that spills through the Andes, in conjunction with enhanced seasonality, continentality and the aforementioned rainshadow effect. The Andean treeline gives way to sparsely vegetated high-Andean grassland and scrubland at ∼700 m.a.s.l. (Lara et al., 2005) in response to colder conditions and prolonged snow cover.

The interface between *Nothofagus* forests and the Patagonian steppe is an extensive biogeographical boundary in southern South America, spanning over 2,000 km along the eastern flank of the Andes Cordillera (e.g., Pisano, 1954; Schmithüsen, 1956; Dimitri, 1972; Donoso, 1998). Palynological studies in areas located within or near the forest-steppe ecotone in southwestern Patagonia (∼45° and 56°S) have related past variations of this boundary with fluctuations in the position and/or intensity of the SWW (Schäbitz, 1991; Heusser, 1993, 1994, 1995; Huber and Markgraf, 2003; Villa-Martínez and Moreno, 2007; Mancini, 2009; Moreno et al., 2009, 2010; Wille and Schäbitz, 2009). These studies document the spread of *Nothofagus* trees eastward into areas formerly occupied by the Patagonian steppe, driven by a regional increase in moisture during the Holocene. The timing, structure, and magnitude of this phenomenon vary across the Andes, distance from the Pacific coast, and among different site types (lakes vs. bogs).

STUDY SITES

Lago Cipreses (51°17′6.15′′S, 72°51′13.48′′W, 1.1 ha, 110 m.a.s.l.) is a small closed-basin lake located on a bedrock depression along the southwestern portion of Lago Toro, ∼85 meters above the current surface of Lago Toro (25 m.a.s.l.) (**Figure 1**). The site is surrounded by mixed forests dominated by the evergreen tree *Nothofagus betuloides* and the deciduous *N. pumilio*, along with the hygrophilous trees *Drimys winteri, Lomatia ferruginea* and the conifer *Pilgerodendron uviferum*. The records from Lago Cipreses span uninterrupted since ∼14.3 ka (ka = 1,000 cal. yr BP) (Moreno et al., 2018). Lago Guanaco (51°52′S, 72°52′W, 200 m.a.sl.) is a small closed-basin lake (∼2 ha) located on a bedrock basin ∼1.5 km north of Lago Sarmiento (**Figure 1**) and ∼28 km north of Lago Cipreses, in Torres del Paine National Park (TPNP) (**Figure 1**). The sedimentary record from Lago Guanaco covers the last 12,600 years (Moreno et al., 2010). Vega Ñandú (50°55′58′′S; 72°45′55′′W; 4 ha, 200 m elevation) is a small mire located ∼12 km north of Lago Guanaco in TPNP (**Figure 1**). Vega Ñandú is situated on a narrow W-E oriented ravine that runs perpendicular to the Río Paine valley, about 50 m above the valley floor. The Vega Ñandú record spans continuously since 12.2 ka to the present (Villa-Martínez and Moreno, 2007). In sum, Lago Cipreses is located on the wet (western) side of the forest/steppe ecotone, whereas Lago Guanaco and Vega Ñandú lie on the dry (eastern) side of the ecotone, the exact position of which has been modified by intensive disturbance by European-set fires and livestock grazing since the nineteenth century (Villa-Martínez and Moreno, 2007; Moreno et al., 2009).

METHODS

We obtained sediment cores using a 5-cm diameter Wright square-rod piston corer (Wright et al., 1984). In the case of Lago Cipreses and L. Guanaco we cored from an anchored raft equipped with 10-cm diameter aluminum casing on the deepest sectors of the lakes. We retrieved the water-sediment interface with a Plexiglas piston corer, which we sampled on site at 1 cm-thick intervals. In the case of Vega Ñandú we obtained the upper meter with a D-section Russian corer and the remaining section with a Wright square-rod piston corer. All sedimentary material was sent to the Quaternary paleoecology laboratory at Universidad de Chile and stored in a cold room at 4°C. We documented the core stratigraphies with the aid of X-radiographs and textural descriptions of the sediments (Villa-Martínez and Moreno, 2007; Moreno et al., 2010, 2018).

The chronology of Lago Cipreses cores is constrained by 15 ^{210}Pb dates and 23 AMS radiocarbon dates performed on bulk lake sediment associated to salient features on the litho- and pollen stratigraphy. In the case of Lago Guanaco we obtained 18 AMS radiocarbon dates on bulk lake sediments and mollusk shells, and in Vega Ñandú 12 AMS radiocarbon dates. We developed Bayesian age models for each site using Bacon for R (Blaauw and Christen, 2011).

We obtained 1-cm thick, 2-cc samples for pollen analysis. All samples were processed following conventional physical and chemical methods that include deflocculation with 10% KOH, sieving (<120 mm), treatment with 40% HF for 30 min in hot water bath, acetolysis and ultrasound (Faegri and Iversen, 1989). The pollen analyses were performed at 400× and 1,000× magnification. Reference material and relevant literature were used to facilitate the identification of pollen, spores (Heusser, 1971; Villagrán, 1980), and microalgal remains. We counted at least 300 pollen grains per level including upland trees, shrubs and herbs (terrestrial pollen sum). The abundance of paludal/aquatic taxa and pteridophytes were added to separate sums, and their percentage values were calculated with reference to the supersums "total pollen" (terrestrial pollen+aquatics) and "total pollen and spores" (total pollen+pteridophytes) respectively. *Nothofagus* in this study refers to the palynomorph *Nothofagus dombeyi* type, which includes three tree species (*N. betuloides, N. pumilio*, *N. antarctica*) that occur in different plant communities throughout SW Patagonia, from sea level to the upper treeline and from the hyperhumid Pacific coast to the forest/steppe ecotone east of the Andes.

We processed macroscopic charcoal samples following the methodology described by Whitlock and Anderson (2003) on the basis of 2-cc sediment samples taken at contiguous 1-cm intervals, deflocculated with 10% KOH and washed through 106-μm mesh screens. Particles were counted in gridded petri dishes under a Zeiss KL1500 LCD stereomicroscope at 50–100× magnification. We conducted time series analysis using CharAnalysis to detect charcoal peaks from the background, and deconvolute a local fire history (Higuera et al., 2009). We interpolated the macroscopic charcoal record at 33-year time windows, the highest median time step between adjacent samples of the three sites (see results section), and defined background charcoal with a lowess robust to outliers and smoothing windows between 500 and 1,000 years, and detected the peaks component with a locally defined threshold that separates the 99th percentile distribution of positive residuals, utilizing a Gaussian mixture model. We calculated the frequency of fire events per 1,000 year overlapping time windows and charcoal peak magnitude.

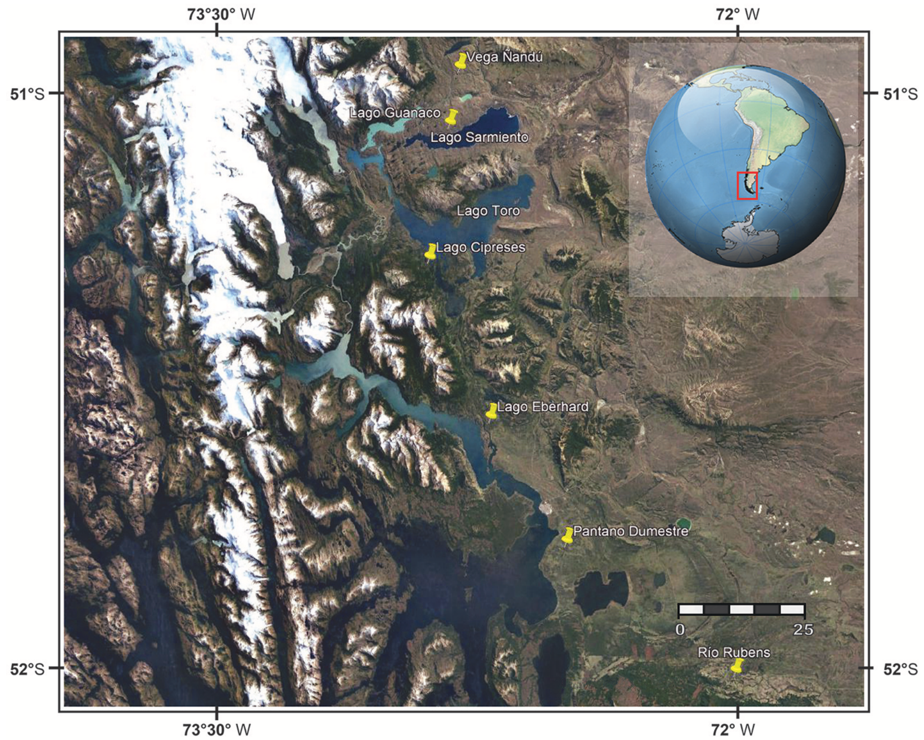

FIGURE 1 | Satellite image of the study area obtained from Google Earth showing the location of the sites discussed in the main text.

RESULTS

This study is based on sediment cores from Lago Cipreses (cores PS0710SC1 + PS0710AT1-3, 365 cm depth) reported in Moreno et al. (2018), Lago Guanaco (cores PS0404SC + PS0711GT1-7, 519 cm depth) reported in Moreno et al. (2010), and Vega Ñandú (cores PS0405RC1A + PS0303AT1-4, 400 cm depth) reported in Villa-Martínez and Moreno (2007). These consist of organic silts in the case of Lago Cipreses and Lago Guanaco, and various transitions from organic mud and peat in the case of Vega Ñandú. The age models suggest continuous high-sediment accumulation rates since 14.3, 12.6, and 12.2 ka, respectively (**Figure 2**). The palynological/macroscopic charcoal records from Lago Cipreses, L. Guanaco and Vega Ñandú feature median time steps between adjacent samples of 33/33, 40/24, and 67/29 years, respectively, allowing a detailed examination of vegetation, fire-regime and climate changes from *Nothofagus* forests currently dominated by evergreen and deciduous species to a xeric steppe in TPNP.

The Lago Cipreses record shows low *Nothofagus* abundance (mean: 13%) prior to 12.7 ka, along with shrubs, herbs, and ferns (Poaceae, Asteraceae, Ericaceae, *Blechnum*), followed by a rapid increase that culminates during a relatively stable plateau (mean *Nothofagus*: 83%) that persists since 11 ka (**Figure 3**). The pollen record from Lago Guanaco shows dominance of shrubs and herbs during much of the record. We observe a gradual rise in *Nothofagus* at 7.8 ka, accompanied by an increase in its hemiparasite *Misodendrum* starting at 6.8 ka (**Figure 3**). Superimposed upon this trend we detect rapid pulses of arboreal expansion at 4, 2.7, 1.4, and 0.6 ka. The *Nothofagus* rise led to maximum abundance between ∼0.6 and 0.1 ka (57%), followed by deforestation by Chilean/European settlers. The Vega Ñandú record shows similar trends to those observed in Lago Guanaco, with larger-amplitude fluctuations and peak *Nothofagus* abundance between 2.4 and 2.1 ka (**Figure 3**). *Nothofagus* exhibits a gradual decline between 2.1 and 0.15 ka and an abrupt decrease associated with European disturbance since then.

The Charcoal Accumulation Rate (CHAR) record from Lago Cipreses features multiple short-lived, large-magnitude increases which correspond with episodes of forest fragmentation and proliferation of understory shrubs, herbs, and ferns (Moreno et al., 2018), with peak frequencies typically at or below 1 event/500 years and frequency maxima at 11 ka, between 9 and 8 ka, and between 5.6 and 3 ka (**Figure 4**). The Lago Guanaco CHAR record shows intermediate values between 13 and 12 ka, low values between 12 and 4 ka with multiple small-magnitude peaks, a rising trend that starts at 4 ka and leads to a variable high-stand with the largest-magnitude peaks over the last 3,000 years (**Figure 4**). Peak frequency maxima are evident between 13 and 10 ka and during the last millennium. Vega Ñandú features predominance of low CHAR values, punctuated by multiple millennial-scale maxima with increasing peak magnitude that culminates at 2 ka. We note a clustering of high-frequency intervals between 12 and 9 ka (**Figure 4**).

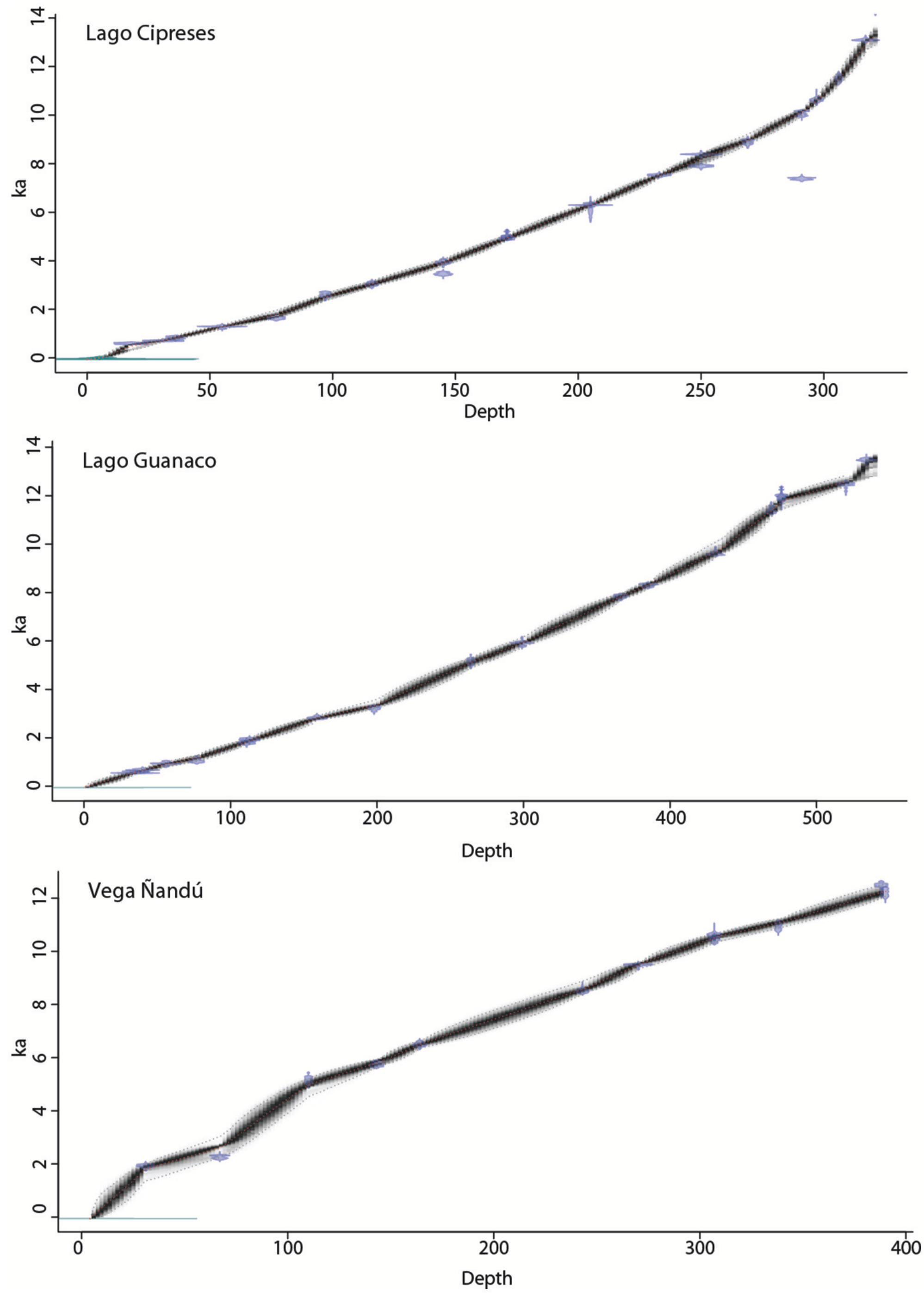

FIGURE 2 | Age models of the sites discussed in this study constructed with the Bacon package for R. The probability distribution of the individual calibrated radiocarbon dates are shown in blue. The 95% confidence of the age model is shown in gray, the median probability age of the age model is shown with a red line.

DISCUSSION

We detect prominent changes in vegetation and fire regimes in southwestern Patagonia since 13 ka (**Figure 3**). In the case of Lago Cipreses, closed-canopy *Nothofagus* forests have persisted since 11 ka with centennial-scale episodes of canopy opening, proliferation and diversification of understory shrubs and herbs, lake-level declines and paleofires (Moreno et al., 2018). Occurrence of paleofires in this humid sector dominated by *Nothofagus* forests is restricted to episodic but recurrent centennial-scale negative anomalies in hydroclimate during the last 11,000 years (Moreno et al., 2018). Sites located in TPNP

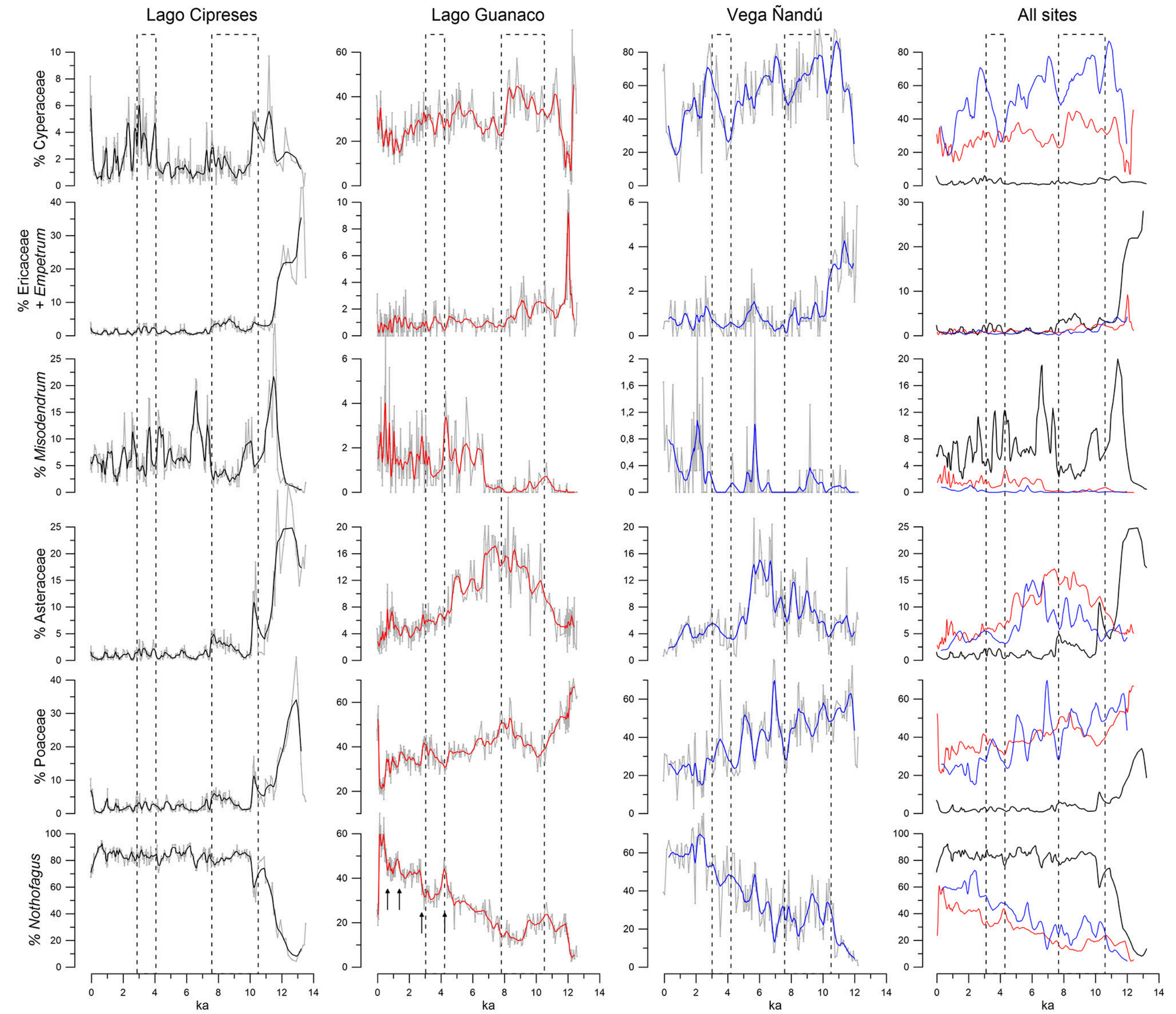

FIGURE 3 | Percentage variation of selected taxa in the sites discussed in this study (fine gray lines) and weighted running means of individual taxa (solid colored lines). The dashed vertical rectangles highlight two conspicuous warm-dry intervals discussed in the Lago Cipreses record.

show dominance of shrubs and herbs (Poaceae, Asteraceae, Ericaceae), along with a gradual and persistent increase in *Nothofagus* since 7.8 ka that reached its maximum during the last two millennia. All sites show onset of Chilean/European disturbance during the mid- to late nineteenth century, with deforestation and spread of exotic herbs (*Rumex*, and possibly *Plantago* and Asteraceae subfamily Cichorioidae) (**Figure 4**). These data indicate that forest vegetation established early during the Holocene in the Lago Cipreses sector (**Figure 3**) and that the forest-steppe ecotone must have lain somewhere between Lago Toro and Lago Sarmiento through much of the Holocene, i.e., between 10 and 26 km north of Lago Cipreses (**Figure 1**). We note that the difference in mean *Nothofagus* abundance between Lago Cipreses (80%) and Lago Guanaco (17%) was highest during the interval between 11 and 7.8 ka ($\Delta = 63\%$) (**Figure 3**), establishing a steep gradient in arboreal pollen during the early Holocene. This gradient declined and reached its minimum during the Little Ice Age ($\Delta = 30\%$ between 0.6 and 0.1 ka) (**Figure 3**) through a series of gradual (between 7.8 and 5 ka) and rapid (5, 2.7, 0.6 ka) increments, oscillations (between2 and 0.6 ka) and abrupt reversals (between 4 and 2.7 ka). We interpret these changes as a sustained encroachment of *Nothofagus* scrubland and woodland, punctuated by rapid pulses of arboreal expansion at 4, 2.7, 1.4, and 0.6 ka, into areas formerly dominated by steppe vegetation. Because the distribution of arboreal vegetation in this sector of southwestern Patagonia is controlled by the amount of precipitation of westerly origin, we interpret increases in *Nothofagus* as enhanced influence

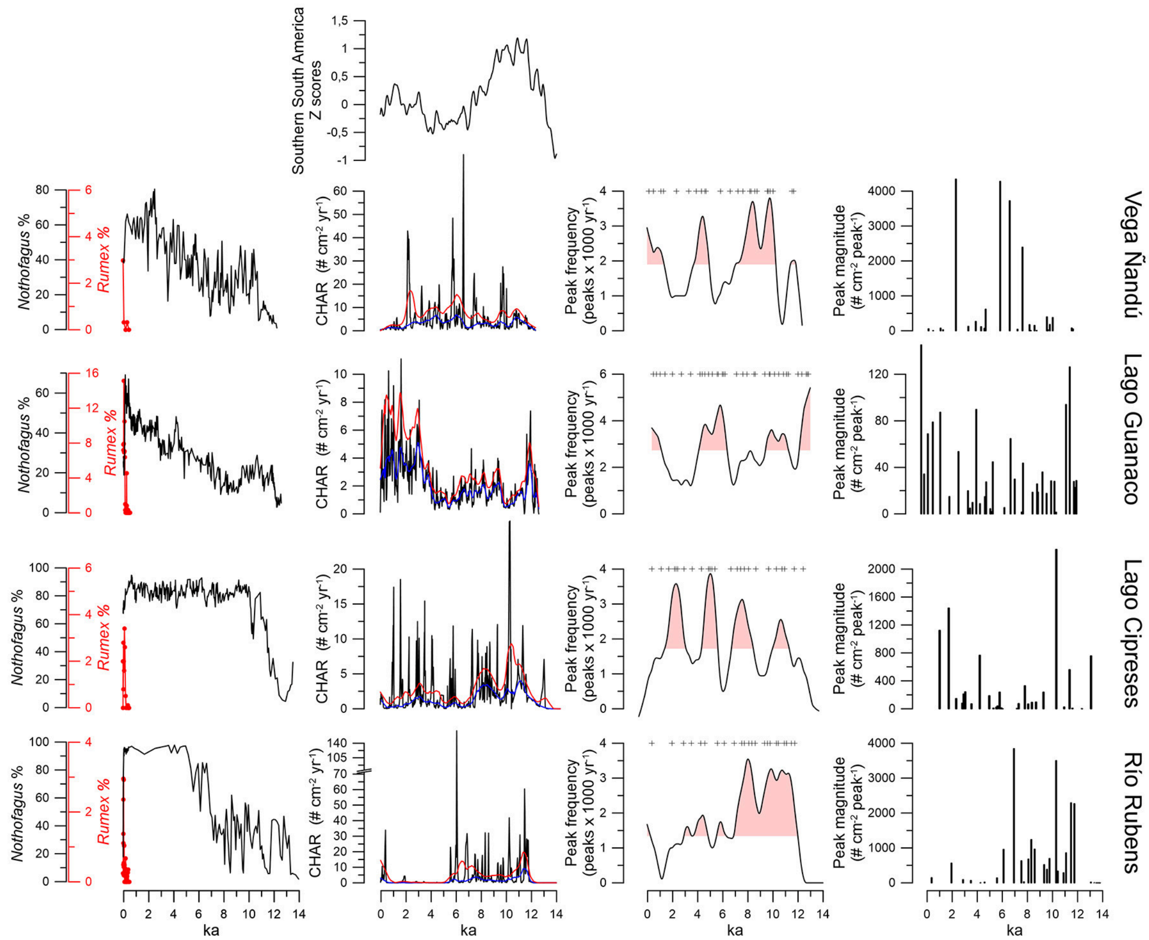

FIGURE 4 | Comparison of the *Nothofagus* and *Rumex* percentages from Lago Cipreses, Lago Guanaco, Vega Ñandú, and Río Rubens, along with their corresponding macroscopic charcoal records and results of CharAnalysis. The black line corresponds to CHAR, the blue line denotes the calculated background, and the red line a locally defined threshold value. The red filling denotes frequency values above the mean in each site, the + symbol represents statistically significant charcoal peaks, the histogram indicates the magnitude of the statistically significant charcoal peaks. Also shown is the charcoal synthesis curve from southern South America normalized to the modern (1–0.1 ka interval) values.

of the SWW at this latitude since 7.8 ka (Moreno et al., 2010).

By virtue of being a fen with a vegetated surface, the Vega Ñandú palynological record incorporates a local (azonal) signal to an airborne extralocal or zonal pollen rain (Villa-Martínez and Moreno, 2007; Moreno et al., 2009). When compared to Lago Guanaco this record not only shows persistently higher abundance of Cyperaceae (**Figure 3**), owing to the minerotrophic and shallow nature of this wetland, but also higher abundance and larger-amplitude fluctuations of *Nothofagus* superimposed on the trends shared with the Lago Guanaco record. One explanation for this behavior is that the species *Nothofagus antarctica*, which establishes the arboreal limit in the forest-steppe ecotone east of the Andes and also thrives in waterlogged substrates, may have grown on the surface of Vega Ñandú increasing its pollen abundance and variability in the sedimentary record (**Figure 3**). We note that peak *Nothofagus* abundance in the Vega Ñandú record was achieved between 2.4 and 2.1 ka, whereas in Lago Guanaco this occurred between ∼0.6 and 0.1 ka (**Figure 3**). This difference could represent the decline of local *Nothofagus* populations growing on the surface of Vega Ñandú in response to a rise in water table during a series of precipitation increases recorded in Lago Guanaco between ∼1.5 and 0.1 ka.

Local fires have taken place repeated times over the last 13,000 years with important variations in the frequency and magnitude of events (**Figure 4**). Likely sources of ignition for these fires include lightning strikes, Native American burning and volcanism. Lightning in western Patagonia is associated to postfrontal convection with a primary maximum along the coast and a secondary maximum along the eastern Andean slopes (Garreaud et al., 2014). To date, unfortunately, we have no proxy for past density of lightning strikes in the stratigraphic record. Because radiocarbon-dated archeological sites in Patagonia suggest that Native Americans have been present in the region consistently since 13 ka (Méndez, 2013), we take this potential source of ignition as a latent driver and assume no major differences in forested vs. landscapes through time along the ~40 km distance separating our study sites. Explosive volcanism can be ruled out as the main driving mechanism for fire occurrence considering that up to five tephras are present in the records (Villa-Martínez and Moreno, 2007; Moreno et al., 2010), and the number of fires in each record is substantially higher than those potentially triggering events. Hence, we consider climate conditions as the main driver of fire activity in this sector of southern Patagonia, and consider lightning strikes and human activities as equally plausible sources of ignition in our study sites since 13 ka.

In Lago Cipreses we observe relatively low fire frequency (overall mean: 1.72 events* 1,000 years^{-1}) and relatively high fire magnitudes, as expected from the local abundance of coarse fuels. Fire occurrence in this forested sector of southwestern Patagonia has been intermittent and is associated with centennial- and millennial-scale warm/dry episodes (**Figure 4**). Frequency maxima occur at 11, 8, 6, and 3 ka, followed by a steady decline until the present. The frequency of local fire events in Lago Guanaco is higher than in Lago Cipreses (overall mean: 2.73 events* 1,000 years^{-1}), with lower-magnitude events (**Figure 4**). Frequency maxima occur at 13, 11-9, 5.5-4 ka and during the last millennium. We observe a trend toward larger-magnitude events from 4 ka onward, in conjunction with successive increases and culmination in the abundance of *Nothofagus* (**Figure 4**). These results suggest that rapid generation and desiccation of fine fuels (shrubs, herbs) in a steppe environment allowed the occurrence of frequent, low-magnitude fires, and that ambient moisture was sufficiently low through most of the record to enable combustion. Increasing levels and continuity of coarse woody fuels since 4 ka, as suggested by the increase in *Nothofagus*, led to higher frequency of events that peaked at 0.3 ka. Vega Ñandú, on the other hand, shows an overall mean of 1.92 local fire events/1,000 years, with a clustering of high-frequency intervals between 10-9, 5.5 ka, and during the last 1,400 years, along with very large magnitude events between 8 and 2 ka (**Figure 4**). We note a divergence in fire regimes between Vega Ñandú and Lago Guanaco despite being located in the same moisture and vegetation zone within the TPNP area, aspect we attribute to local burning of vegetation and/or organic deposits at the surface of Vega Ñandú. Ground and underground fires in wetlands is a common phenomenon is southwestern Patagonia at times of lowered water table, as the fire fronts sweep through the landscape aided by strong summer winds. Thus, taphonomic processes in bogs can potentially overprint extralocal or regional signals, overemphasizing a local or azonal signal.

We carried out time series analysis of the macroscopic charcoal record from Río Rubens bog (Huber et al., 2004) to compare with our records (**Figure 4**), interpolating samples at 33-year intervals. High CHAR values are evident prior to ~5.5 ka, with a broad maximum in fire frequency between 11.5-7.5 ka and very large-magnitude events between 12-6 ka. This was contemporaneous with dominance of steppe herbs and shrubs during the minerotrophic phase of the site (Huber et al., 2004). Fires become absent or rare after ~5.5 ka, coeval with increased arboreal abundance (**Figure 4**) and a shift to ombrotrophic conditions. Renewed fire activity over the past ~400 years overlaps with European settlement and appearance of *Rumex*. We observe that bog sites (Vega Ñandú and Río Rubens) share high fire frequency intervals between 10-8 ka and at ~4.5 ka, along with very large-magnitude fire events between 8-6 ka (**Figure 4**). Lake records show a similar, though much diminished peak in fire frequency and substantially lower magnitude of events during the same interval, even in the case Lago Cipreses which shows dominance of forest vegetation. From this comparison we conclude that charcoal records from bogs tend to overestimate fire occurrence by surface burning at times of lowered precipitation and water table.

Regional Implications

Broad-scale syntheses show a conspicuous enhancement of fire activity during the early Holocene in southern South America (Whitlock et al., 2007; Power et al., 2008) (**Figure 4**), and southwestern Patagonia in particular (Huber et al., 2004), followed by a generalized decline and spatial heterogeneity between 9.5 and 6 ka, and intensification of that variability during the last 3,000 years. We observe that these signals are not prominent features in the macroscopic charcoal records from Lago Cipreses, L. Guanaco and Vega Ñandú (**Figure 4**), suggesting that the broad scale signal revealed by the regional synthesis of (predominantly) microscopic charcoal records is modulated by contingencies at smaller spatial scales. Our charcoal records from TPNP, however, do show multiple maxima in the frequency of local fires during the early Holocene (11-7.5 ka), compatible with Huber et al. (2004)'s observation of high fire activity during this interval (**Figure 4**). Also, the southern South American charcoal curve (Power et al., 2008) shows a sustained rise from the lowest Holocene values starting at 4 ka, in agreement with the Lago Guanaco CHAR record (**Figure 4**).

Previously published macroscopic charcoal records from Lago Eberhard and Pantano Dumestre (Moreno et al., 2012), located 35 and 65 km SE from Lago Cipreses respectively (**Figure 1**), show a major increase in fire frequency at the beginning of the Holocene (11.5 ka). Unlike Lago Eberhard, the Pantano Dumestre record shows a major increase in the magnitude of local fires contemporaneous with a regressive lake phase that led to terrestrialization of the site and forest encroachment early during the Holocene. These findings, along with the previous discussion, suggest to us that macroscopic charcoal records from bogs and fens, e.g., the Río Rubens site (**Figure 4**) (Huber et al., 2004) yield a paleofire signal skewed toward surface burning of the bogs themselves, blurring the extralocal or regional fire-regime signal. We acknowledge, however, that our conclusions are based only on a few detailed time series of continuous/contiguously sampled macroscopic charcoal records from small closed-basin lakes.

We posit that taphonomic differences could account, to a large extent, for the apparent divergence in vegetation and climate histories among previously published records from lakes and bogs in southwestern Patagonia. One of those divergences is evident between the pollen records from Cerro Frías (Mancini, 2009) and Lago Guanaco, sites separated by 70 km along the eastern Andean slopes of southwestern Patagonia. The Cerro Frías record shows continuous deposition in a Cyperaceae fen since 12 ka and a steady increase in *Nothofagus* between ∼11 and 3 ka, in agreement with the lake-sediment-based pollen record from Lago Guanaco. *Nothofagus* attained its maximum at 3 ka in Cerro Frías and then started a sustained decline until its minimum Holocene values during the recent centuries (Mancini, 2009). The Lago Guanaco record, on the other hand, shows rapid increases at 2.7 and 0.6 ka which led to a *Nothofagus* maximum between 0.6 and 0.1 ka (**Figures 3**, **4**). These results were interpreted as a decline in temperature (Mancini, 2009) and precipitation (Tonello et al., 2009) over the last ∼3,000 years in the case of the Cerro Frías record, and as an increase in precipitation in Lago Guanaco (Moreno et al., 2009, 2010), coherent with the Vega Ñandú (Villa-Martínez and Moreno, 2007) and Lago Cipreses (Moreno et al., 2018) records. These interpretations were, in turn, attributed to weaker (Cerro Frías) or stronger (Lago Guanaco, Vega Ñandú, Lago Cipreses) SWW influence over the last 3,000 years for sites located only 70 km apart. We posit that the differences between the Lago Guanaco and Cerro Frías pollen records could represent a decline in *Nothofagus* trees growing on the surface of the Cerro Frías fen, driven by a rise in local water table associated with increased precipitation of SWW origin during the last 3,000 years, as illustrated by the Lago Guanaco, Vega Ñandú and Lago Cipreses records.

SUMMARY AND CONCLUDING REMARKS

The data shown in this paper suggests that vegetation type exerts an important influence on fire regimes (local fire event frequency and magnitude) through the Holocene along a short transect (∼28 km) through the forest-steppe ecotone in southwestern Patagonia. We also detect significant differences between vegetation and fire histories developed from a lake and a bog in TPNP, and conclude that differences in taphonomic processes produce a signal skewed toward local (azonal) conditions in the case of bogs.

Our lake-sedimentary data are consistent with findings based on relative area burned over a 25-year period along a latitudinal transect of 3,300 km through southwestern South America (between 25°S and 56°S) (Holz et al., 2012). Our findings expand upon those results and suggest that vegetation differences at the landscape level have also determined the nature of climate-fire relationships at timescales ranging from multi-decadal to multi-millennial.

AUTHOR CONTRIBUTIONS

PM and RV-M designed the study and carried out initial analyses. IV developed the pollen record from Lago Cipreses. RV-M developed the pollen record from Vega Ñandú. JF developed the pollen and charcoal record from Lago Guanaco. PM wrote the paper with contributions from all coauthors.

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