Disentangling the last 1,000 years of human–environment interactions along the eastern side of the southern Andes (34–52°S lat.)

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Contributed by Cathy Whitlock; received October 29, 2021; accepted January 11, 2022; reviewed by Luis Borrero, Thomas Kitzberger, and Vera Markgraf

Researchers have long debated the degree to which Native American land use altered landscapes in the Americas prior to European colonization. Human–environment interactions in southern South America are inferred from new pollen and charcoal data from Laguna El Sosneado and their comparison with high-resolution paleoenvironmental records and archaeological/ethnohistorical information at other sites along the eastern Andes of southern Argentina and Chile (34–52°S). The records indicate that humans, by altering ignition frequency and the availability of fuels, variously muted or amplified the effects of climate on fire regimes. For example, fire activity at the northern and southern sites was low at times when the climate and vegetation were suitable for burning but lacked an ignition source. Conversely, abundant fires set by humans and infrequent lightning ignitions occurred during periods when warm, dry climate conditions coincided with ample vegetation (i.e., fuel) at midlatitude sites. Prior to European arrival, changes in Native American demography and land use influenced vegetation and fire regimes locally, but human influences were not widely evident until the 16th century, with the introduction of nonnative species (e.g., horses), and then in the late 19th century, as Euro-Americans targeted specific resources to support local and national economies. The complex interactions between past climate variability, human activities, and ecosystem dynamics at the local scale are overlooked by approaches that infer levels of land use simply from population size or that rely on regionally composited data to detect drivers of past environmental change.

paleoecology | southern South America | fire history | human–environment | vegetation history

Understanding the contribution of people in shaping landscape history through their use of fire is a fundamental component of human–environment research and critical for conservation and land-management strategies that seek to maintain elements of pre-European ecosystem dynamics into the future (1, 2). In North and South America, discussions centered around this topic have become increasingly nuanced, acknowledging that the interactions between climate, human activity, and ecosystem dynamics are complex and vary at different temporal and spatial scales (e.g., refs. 3 and 4). In most ecosystems, fire is the dominant type of natural disturbance, but fire has also long been used by humans to facilitate hunting, forest clearance, resource enhancement, and defense. Such strategies have increased ignitions and altered the length and timing of fire seasons (1), but less clear in many regions is the contribution of human-set fires in shaping climate–vegetation dynamics over time.

A long-term perspective on fire comes largely from paleoecological and archaeological records that span millennia, although interpretation of these data are often confounded by the uneven distribution of records and their low sampling resolution, poor chronological control, and unclear spatial inference. Ethnographic and historical accounts provide additional information on anthropogenic burning, but they generally describe Native American activities following the spread of European diseases and attendant population declines; the introduction of livestock, crops, and horses; and the cultural changes following genocide and enforced confinement (5–8). These accounts may not be representative of longer patterns of use.

The forest–steppe boundary on the eastern side of the Andes in southern South America is one of the sharpest ecotones on Earth and shaped by a combination of climate, fire, and human activity (9). Although many studies along the ecotone have focused on the long-term fire and vegetation history (10–12) and recent human–fire interactions (13, 14), relatively little is known about the ecosystem dynamics of the region during the

Significance

Understanding how people have shaped landscapes requires detailed information on past changes in climate, vegetation, fire, and land use. The environmental and human history of four sites along the eastern Andes of southern South America (34–52°S) shows the changing influence of people and climate on landscape development over the last millennia. Initially, burning by hunter-gatherers and climate variability shaped forest, shrubland, and grassland mosaics. Widespread alteration of fire regimes and vegetation ~400 y ago is attributed to increased Native American pastoralism prior to extensive Euro-American settlement. Late-19th century ranching and logging led to broadscale changes in fire activity and vegetation across the region. These high-resolution, landscape-scale reconstructions reveal complex human–environment interactions that are often overlooked in regional-to-global syntheses.

Author contributions: W.N. and C.W. designed research; W.N. and C.W. performed research; W.N. and D.N. analyzed data; and W.N., C.W., M.E.d.P., A.G., D.N., and G.N. wrote the paper.

Reviewers: L.B., Consejo Nacional de Investigaciones Científicas y Técnicas; T.K., Instituto de Investigaciones en Biodiversidad y Medioambiente, Consejo Nacional de Investigaciones Científicas y Técnicas, Universidad Nacional del Comahue; and V.M., Northern Arizona University.

The authors declare no competing interest.

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This article contains supporting information online at http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2119813119/-/DCSupplemental.

Published February 22, 2022.

transition from Native American to Euro-American land use practices in the last 1,000 y. This gap in knowledge stems from the short duration of most tree-ring records of fire (spanning a few centuries), the paucity of archaeological data to connect with historical and ethnographic information, and the low temporal and spatial resolution of paleoecological records during this time span.

To address these shortcomings, we present high-resolution pollen, charcoal, and lithological records from Laguna El Sosneado in Mendoza Province, Argentina, to describe the late-Holocene vegetation and fire history in a location with abundant archaeological sites. We compared the ecological history of the last 1,000 y at this and three other sites (Laguna Portezuelo, Lago Mosquito, and Río Rubens Bog) along the east side of the Andes from latitude 34–52°S. These four sites were selected because of their well-constrained age-depth models, exceptionally high-resolution pollen and charcoal records for the last ∼1,000 y, and varying degrees of Native American and Euro-American land use (Fig. 1 and Table 1). Their comparison enables a broader understanding of the human–climate drivers of past environmental change along a north-to-south climate gradient.

Present and Past Climate along the Southern Andes

The climate along the eastern flank of the southern Andes is largely governed by a steep moisture gradient that results from the interception of Pacific storms, tracking the path of the southern westerly winds (SWW), by the north–south-trending Andes. The west-to-east decline in moisture is evidenced by the sharp vegetation transition from evergreen to deciduous forest and then to grass- to shrub-steppe over a distance of ∼100 km (Fig. 1). The north-to-south climate gradient is a result of latitudinal temperature differences as well as seasonal changes in the location of the SWW and its effect on precipitation and vapor pressure. The SWW shift northward during the austral winter (May to August), leading to a winter-dominated precipitation regime between ∼32 and 45°S (i.e., Laguna El Sosneado, Laguna Portezuelo, and Lago Mosquito), and southward during austral summer (December to February) directing storm tracks south of 48°S (i.e., providing increased summer precipitation near Río Rubens Bog) (23). Low-pressure systems from the subtropical Atlantic and Amazon Basin also extend farther south during austral summer and result in convective storms north of ∼40°S; these storms are the main source of lightning in the region (23). Lightning frequency in the study region is low (<0.5 strikes km^{-2} y^{-1} between 2010 and 2020 years Common Era [CE]), but slightly higher in the north than the south (22, 24) (Fig. 1), and most fires today are human-set (14). The climate of each site from 1901 to 2018 CE is presented in Table 1.

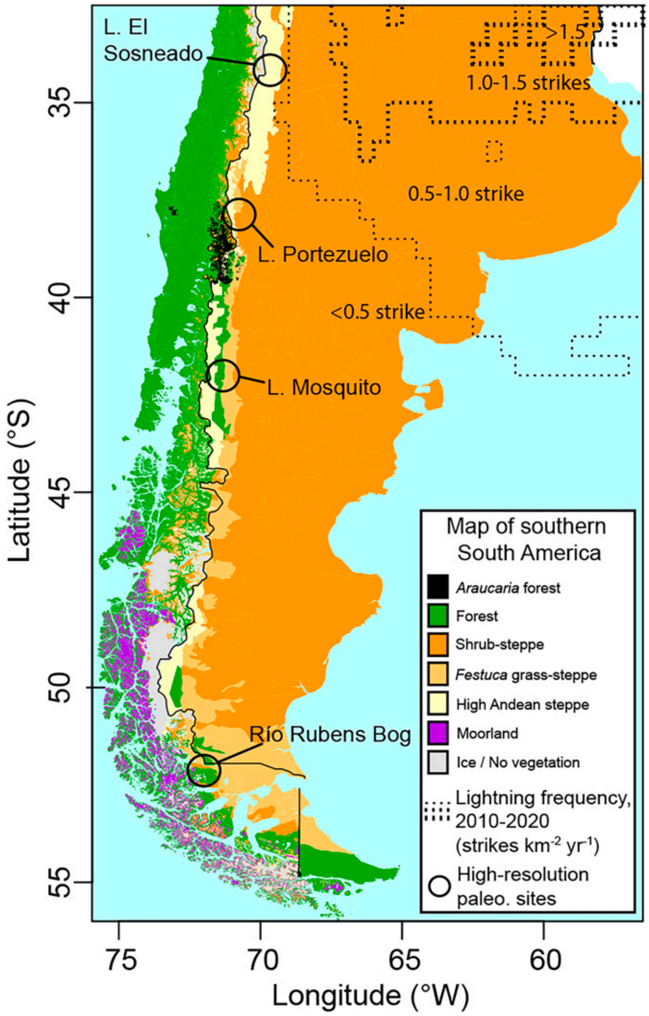

Fig. 1. Map of southern South America showing vegetation zones based on refs. 19–21, lightning frequency (2010 to 2020, strikes km^{-2} y^{-1}) (22), and locations of the high-resolution paleoecological sites discussed in the text and in Table 1.

The north–south climate differences are modulated by interannual climate variability driven by the El Niño-Southern Oscillation (ENSO; mainly north of 41°S) and southern annular mode (SAM; mainly south of 20°S). El Niño and the negative phase of SAM result in warmer-than-average annual temperatures and increased annual precipitation along the east side of the southern Andes in the north, because SWW storm tracks are generally shifted north of their mean position. In contrast, La Niña and the positive phase of SAM promote cooler-than-average annual temperatures and decreased annual precipitation, because SWW storm tracks are shifted southward (23, 25).

Paleoclimatic data document millennial-scale shifts in temperature and the strength and position of the SWW over the last 18,000 y (the end of the last glaciation) and indicate that generally modern conditions were established about 4,000 y ago (the late Holocene) (26–28). Superimposed on this long-term climate trend, the region has also experienced short-term variations in climate during the late Holocene. Reconstructed temperatures from tree-ring studies (29) and stable isotope data (30) show warmer conditions between ∼1150 and 600 calibrated years before present (cal y BP; 800 to 1350 CE) during the Medieval Climatic Anomaly (MCA; ∼1000 to 700 BP) (31), and cooler temperatures than present between ∼600 and 200 cal y BP (1350 to 1750 CE) during the Little Ice Age (LIA; ∼550 to 250 BP) (31). Self-calibrated Palmer Drought Severity Index reconstructions from between 550 and 200 BP (scPDSI; 1400 to 1750 CE) (32) suggest that moisture levels varied during the LIA, with generally wet conditions in the north (i.e., Laguna El Sosneado, Laguna Portezuelo), intermediate conditions in the central region (i.e., Lago Mosquito), and dry conditions in the south (i.e., Río Rubens Bog) (*SI Appendix*, Fig. S1). (Note that henceforth, dates from the last 2,000 y will be presented in BCE/CE, as well as cal y BP, where "present" is 1950 CE.)

Interannual climate variability driven by changes in the strength of ENSO (both El Niño and La Niña) and SAM has also changed during the late Holocene. ENSO was strongest between ∼50 BCE and 1250 CE (2000 to 700 cal y BP), weak from ∼1250 to 1900 CE (700 to 50 cal y BP), and then strong again in the last century (33). Tree-ring records indicate that ENSO has affected interannual precipitation and fire activity along the forest–steppe ecotone of southern South America (29, 32, 34). SAM was in a negative phase during the 15th century CE and has become more positive since ∼1940 CE (10 cal y BP), resulting in increasingly dry interannual conditions at high latitudes in southern South America (23, 25, 32).

Table 1. Information about the study sites

Site name	Latitude (°S)	Longitude (°W)	Elevation (m)	Temperature (°C)*	Precipitation (mm y^{-1})*	Vapor pressure (hPa)	Age constraint (last 1,000 y)	Median resolution (y $sample^{-1}$)†	Pre-European vegetation	Source
Laguna El Sosneado	34.8	69.9	2110	5.6	524	3.6	3	Pollen = 24 Charcoal = 8	Grass-, shrub-steppe	Present work
Laguna Portezuelo	37.9	71.0	1730	7.2	618	4.5	4	Pollen = 16 Charcoal = 16	Steppe with patches of *Araucaria*	Nanavati et al. (15)
Lago Mosquito	42.5	71.4	560	6.8	697	5.3	5	Pollen = 19 Charcoal = 6	*Austrocedrus chilensis*-*Nothofagus dombeyi* woodland and steppe	Present work, Whitlock et al. (16)
Río Rubens Bog	52.0	71.9	220	6.7	389	6.2	10	Pollen = 16 Charcoal = 18	Open *N. antarctica* and *N. pumilio* forest and steppe	Huber and Markgraf (17) Markgraf and Huber (12)

*Annual median values (1901 to 2018) from CRU 4.05 0.5° grid cells (18).
†Estimated from ~1,000 cal y BP to the core top.

Human History along the Southern Andes

Native Americans were present along the coast of southern South America by ~14,500 cal y BP (35, 36) and east of the Andes by ~12,800 cal y BP (35, 37, 38). The archaeological record suggests that populations east of the Andes were small, dispersed, and reliant on nomadic hunter-gatherer subsistence strategies until the late Holocene (36, 38–40). In the late Holocene, archaeological assemblages were more diverse and numerous, suggesting that a wider range of taxa were exploited by potentially a larger population (e.g., refs. 41–44). West of the Andes, the Mapuche peoples practiced a combination of hunter-gatherer-forager and intensive agricultural subsistence strategies. Although Native American groups traveled across the Andes for hunting and exchange, Spanish conquest of the Chilean coast beginning in the late 16th century and later conflicts in the 18th and 19th centuries may have increased the translocation of Mapuche peoples to east of the Andes. Their greater and persistent presence on the east side brought increased sedentism and horticultural practices, especially in northern Patagonia (36–45°S) (45–47).

Europeans first interacted with Native Americans in southern South America in 1520 CE (430 cal y BP). Spanish Colonial (1532 to 1818 CE; 418 to 132 cal y BP) settlement occurred slowly and was strategically situated to facilitate and control trade (5, 48). Native American groups took advantage of European crops, horses, and other livestock by the end of the 16th century and modified their subsistence strategies and settlement patterns to accommodate new agricultural and pastoral opportunities (6, 7, 49–51). According to 19th century travelers, many Native American groups in southern South America used fire to signal distant parties, facilitate hunting, and improve forage for native and nonnative grazers (8, 50, 52). During the 19th century, the Argentine and Chilean governments actively encouraged Euro-American settlement of the region, primarily for farming and ranching. Subdivision of Native American lands resulted in conflict and ultimately precipitated the displacement and genocide of Native American groups in the late 19th century (5, 39).

Results

Pollen and charcoal data, spanning the last 3,600 y from Laguna El Sosneado, provide records of vegetation and fire history in the Mendoza region of the Andes. At present Laguna El Sosneado lies within a heavily grazed grass- and shrub-steppe with the nearest forest to the west of the Andean crest (Table 1). Herbaceous steppe species include *Stipa chrysophylla*, *Poa ligularis*, and *Tropaeolum incium*. The dominant shrubs are *Adesmia pinnifolia*, *Anarthrophyllum rigidum*, *Baccharis darwinii*, *Chuquiraga oppositifolia*, *Ephedra triandra*, *Nassauvia axillaris*, *Pantacantha ameguinoi*, *Schinus polygama*, *Senecio filaginoides*, and *Senna arnottiana*. The lake margin supports Amaranthaceae, *Azorella trifurcata*, *Cortaderia* spp., Cyperaceae, *Juncus* spp., *Plantago*, Ranunculaceae, and scattered *B. darwinii* and *S. polygama*; aquatic *Myriophyllum*, *Potamogeton*, and *Typha* grow in the littoral zone.

Between ~3600 and 2000 cal y BP, the pollen record features high pollen percentages of Poaceae and Asteroideae pollen, the presence of *Ephedra* and *Schinus* pollen, and moderate-to-high charcoal accumulation rates (CHAR; particles cm^{-2} y^{-1}) (Fig. 2). The data indicate the presence of shrub- and grass-steppe vegetation with greater herbaceous cover than present, thus providing sufficient biomass and fuel connectivity to support frequent, low-severity fires. Between 50 BCE and 1150 CE (2000 to 800 cal y BP), increased Asteroideae and *Schinus* pollen at the expense of Poaceae suggests less herbaceous cover and drier conditions. Moderate CHAR values and increased variability in the wood:grass charcoal ratios at this time indicate that, although there was fuel for fires, a loss in fine fuels resulted in patchier fires than before. Between ~1150 and 1450 CE (800 to 500 cal y BP), Asteroideae pollen accumulation rates (PAR; grains cm^{-2} y^{-1}) (*SI Appendix*, Fig. S2) decreased and Poaceae PAR remained stable (resulting in an increase in Poaceae pollen percentages). This shift implies greater herbaceous cover and possibly wetter conditions than before. CHAR values abruptly decreased after ~1280 CE (670 cal y BP), indicating fewer fires than before, and fluctuations in the wood:grass charcoal ratio suggest shifts in fuel biomass. An expansion of Asteroideae and *Schinus* shrubs and a decrease in fire occurred between ~1450 and 1800 CE (500 to 150 cal y BP), as evidenced by high pollen percentages and PAR and lower CHAR values than before (Fig. 2 and *SI Appendix*, Fig. S2). Nonnative pollen taxa increased in abundance in the last two centuries: *Rumex* at ~1750 CE (200 cal y BP; 95% highest posterior density [HPD] interval = 440 to 71 cal y BP); *Plantago* at ~1880 CE (70 cal y BP; 95% HPD interval = 162 to 20 cal y BP); Cichorioideae at ~1955 CE (−5 cal y BP; 95% HPD interval = 11 to −31 cal y BP); and *Pinus* at ~1978 CE (−28 cal y BP; HPD interval = −17 to −46 cal y BP). In the last century, pollen from Asteroideae and Rhamnaceae increased at the expense of *Schinus* and Poaceae. CHAR values peaked at ~1950 CE (0 cal y BP) and then decreased to very low levels after ~1960 CE (−10 cal y BP). The charcoal data imply significant burning in the mid-20th century followed by a decline in fires in recent decades. Further results and interpretations of the Laguna El Sosneado record are provided in *SI Appendix*.

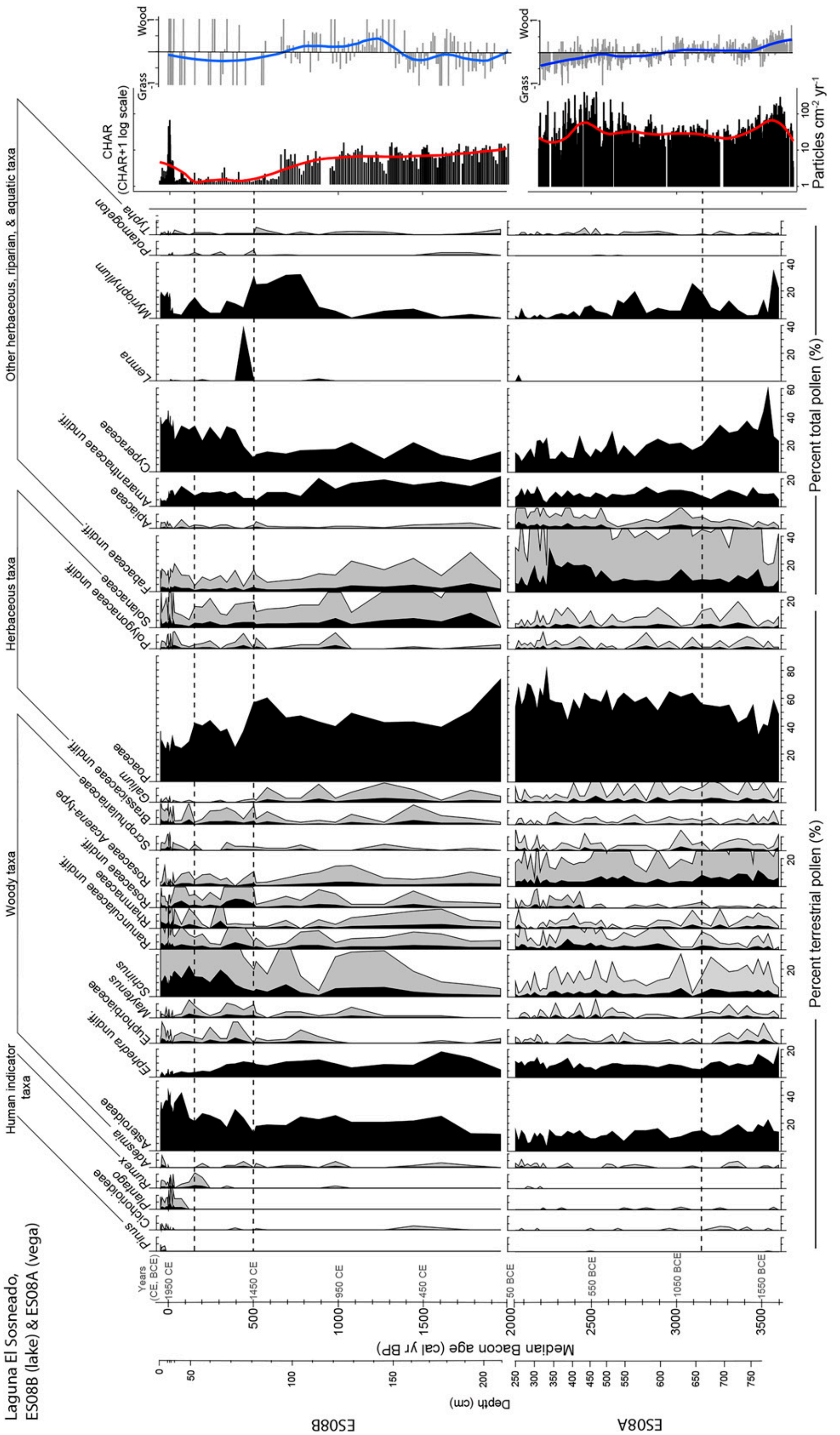

Fig. 2. Pollen percentage diagram from Laguna El Sosneado (ES08A and ES08B cores) showing pollen taxa and zones discussed in text (gray shading indicates a 5× exaggeration). CHAR (black), background CHAR (BCHAR; red), grass:wood charcoal ratio (gray bars with smoothed blue line) describe variations in fire activity.

Discussion

The vegetation and fire history of the last 1,000 y, reconstructed from the four pollen and charcoal records, is interpreted in light of independent paleoclimatic records (e.g., refs. 25, 30, and 32) and archaeological and ethnohistorical information (e.g., 5, 41, and 49–52). To understand the role of climate and humans in shaping site-specific vegetation histories, we assume that the impact of climate on past vegetation and fire activity varied across this latitudinal moisture gradient, just as it does at present. Although lightning is generally infrequent throughout the region, it becomes rarer to the south. We therefore infer that human ignition was increasingly important at higher latitudes in southern South America during the last 1,000 y. As such, the northern site (Laguna El Sosneado) would have the most fires during cool, moist periods when development of fine fuels would have facilitated fire spread; both lightning and humans may have been the source of ignition. Conversely, fires at midlatitudes (Laguna Portezuelo and Lago Mosquito) and high latitudes (Río Rubens Bog) would have occurred during warm, dry periods as a result of increased fuel flammability; ignition, especially in southern Patagonia, was likely anthropogenic.

Laguna El Sosneado. Prior to the last 1,000 y, the late-Holocene vegetation and fire history from Laguna El Sosneado was characterized by grass- and shrub-steppe with moderate-to-high fire activity (Fig. 2). Shifts in vegetation and levels of burning near Laguna El Sosneado in the last 1,000 y are attributed to a combination of changes in climate and human activity (Fig. 3*A*). During the MCA, the charcoal data indicate moderate levels of burning, and these fires maintained a shrub-grass mosaic. Early fire activity was facilitated by warm, dry conditions and a mixture of woody and herbaceous fuel types, with Native Americans serving as an important source of ignition. Archaeological assemblages near Laguna El Sosneado in the Río Atuel Valley indicate that the local area was occupied by dispersed and nomadic hunter-gatherers since ~9000 cal y BP. After ~4000 cal y BP, archaeological assemblages became more diverse and numerous, suggesting a larger population (e.g., refs. 41–43). During the last ~2000 cal y BP a wider range of taxa were exploited by hunter-gatherers, supplementing guanaco hunting with plants, small mammals, and birds. The abandonment of archaeological sites near Laguna El Sosneado and at higher elevations in the region suggests that Native American populations likely moved to lower elevations between 1350 and 1450 CE (600 to 500 cal y BP) and were later reduced because of the spread of European diseases following the arrival of the Spanish to the region (53, 54).

A sharp decrease in fire activity at ~1280 CE (670 cal y BP) persisted through ~1930 CE (20 cal y BP). This loss of fire preceded the decline of grass cover, the onset of lower LIA temperatures, and a brief period of very dry conditions between ~1450 and 1560 CE (500-390 cal y BP), as inferred from scPDSI values (Figs. 2 and 3*A* and *SI Appendix*, Fig. S1*A*). LIA cooling in this dry region should have favored fire by generally increasing effective moisture (as seen in *SI Appendix*, Fig. S1*A*) and, as a result, fuel cover, but the charcoal record suggests the opposite. A shortage of ignitions may have been a limiting factor for fire activity, either as a result of land abandonment, a change in land use, or fewer convective storms. An increase of *Schinus* in the pollen record after ~1560 CE (390 cal y BP) occurs at a time when conditions became wetter following the drought period (Fig. 2 and *SI Appendix*, Fig. S1*B*). *S. polygama* was an important resource for food (its berries), fuel, and construction materials for corrals with the adoption of seasonal pastoralism (6, 41, 55). The appearance of human indicator taxa after ~1750 CE (200 cal y BP) coincides with increased trade between local Native American groups and Spanish Colonial settlements, as well as cattle, sheep, and horse pastoralism throughout the region (Figs. 2 and 3*A*) (45). The increase in pollen from unpalatable Asteroideae and Rhamnaceae shrubs (e.g., *B. darwinii*, *S. filaginoides*, and *Colletia spinosissima*) at the site after ~1830 CE (120 cal y BP) suggests a landscape heavily grazed during early Euro-American settlement. We attribute the brief return in high fire activity between ~1950 and 1960 CE (0 to −10 cal y BP) to recent Euro-American land use. Thus, the Laguna El Sosneado record suggests that people and climate both shaped local vegetation and fire history prior to the mid-18th century, but land use was the predominant driver of ecosystem dynamics in the last 200 y.

Laguna Portezuelo. The pollen and charcoal data from Laguna Portezuelo indicate the presence of an open, forest–steppe ecotonal landscape and steady fire activity through much of the Holocene (Fig. 3*B*) (15). Rising pollen percentages of *Nothofagus* after 6590 cal y BP suggest more forest cover and increased moisture in the late Holocene. A striking absence of fire in the Laguna Portezuelo record between ~50 BCE and 1580 CE (2000 to 370 cal y BP) suggests a period of limited human and natural ignitions despite the presence of fuel-rich vegetation suitable for burning (Fig. 3*B*). Although the archaeology near Laguna Portezuelo warrants further study, research elsewhere along the forest–steppe ecotone of central and northern Neuquén suggests that dispersed and nomadic hunter-gatherers were present near the site by ~12,500 cal y BP. During the late Holocene, archaeological assemblages become more diverse and numerous, suggesting rapidly increasing populations (36, 38).

Araucaria pollen increased in abundance after ~1580 CE (370 cal y BP), in association with increasing CHAR. The expansion of *Araucaria araucana* woodland and fires coincides with a time of increased interannual climate variability and immigration of Mapuche Native Americans from the Chilean coast and foothills (Fig. 3*B* and *SI Appendix*, Fig. S1*B*). Ethnohistorical records indicate that Pehuenche and Mapuche groups in the region used fire to facilitate hunting and gathering, to signal neighboring groups, and for ceremonial purposes (56). Between ~1580 and 1890 CE (370 to 60 cal y BP), the pollen and charcoal data show a rise in *Nothofagus* and *Araucaria*, the first appearance of nonnative *P. lanceolata* and *R. acetosella*, and dramatically increased CHAR levels. These changes coincided with the cool, relatively moister conditions of the LIA and increased pastoralism and horticulture related to the greater presence of Mapuche populations east of the Andes. We suggest that fire activity after ~1580 CE (370 cal y BP) was amplified by climate-driven increases in fuel load during the LIA and in anthropogenic ignitions. *A. araucana* was of great cultural and resource significance to Mapuche and Pehuenche peoples (53), and evidence of its increase and more fires after ~1580 CE (370 cal y BP) suggests local silvicultural management through deliberate burning (15). Tree-ring records near Laguna Portezuelo also indicate frequent fires at ~6-y intervals during Mapuche–Pehuenche occupation (57).

The further increase of nonnative pollen types at the expense of *Nothofagus* and *Araucaria* pollen after ~1890 CE (60 cal y BP) is associated with local Euro-American settlement, increased grazing and logging, and the establishment of commercial *Pinus* plantations in the mid-20th century (Fig. 3*B*). Thus, the human signature of fire in the Laguna Portezuelo region became evident in the late 16th century when changes in vegetation were likely facilitated by cooler moister conditions as well as deliberate burning. Euro-American deforestation and use of fire are clear in the paleoecological record starting in the late 19th century.

Lago Mosquito. The pollen record from Lago Mosquito indicates the establishment of mixed *Nothofagus–Austrocedrus* forest in last 3,600 y. *Austrocedrus* reached its highest abundance between ~2670 and 1380 cal y BP and after ~1750 CE (210 cal y BP) (16). Archaeological evidence from ~100 km north of Lago Mosquito suggest the regional presence of dispersed and nomadic hunter-gatherers as early as ~12,500 cal y BP. The earliest archaeological sites near Lago Mosquito demonstrate nearly continuous occupation since ~3100 cal y BP, as well as the exchange of rock art motifs that suggest a prolonged interaction between Native American groups east and west of the

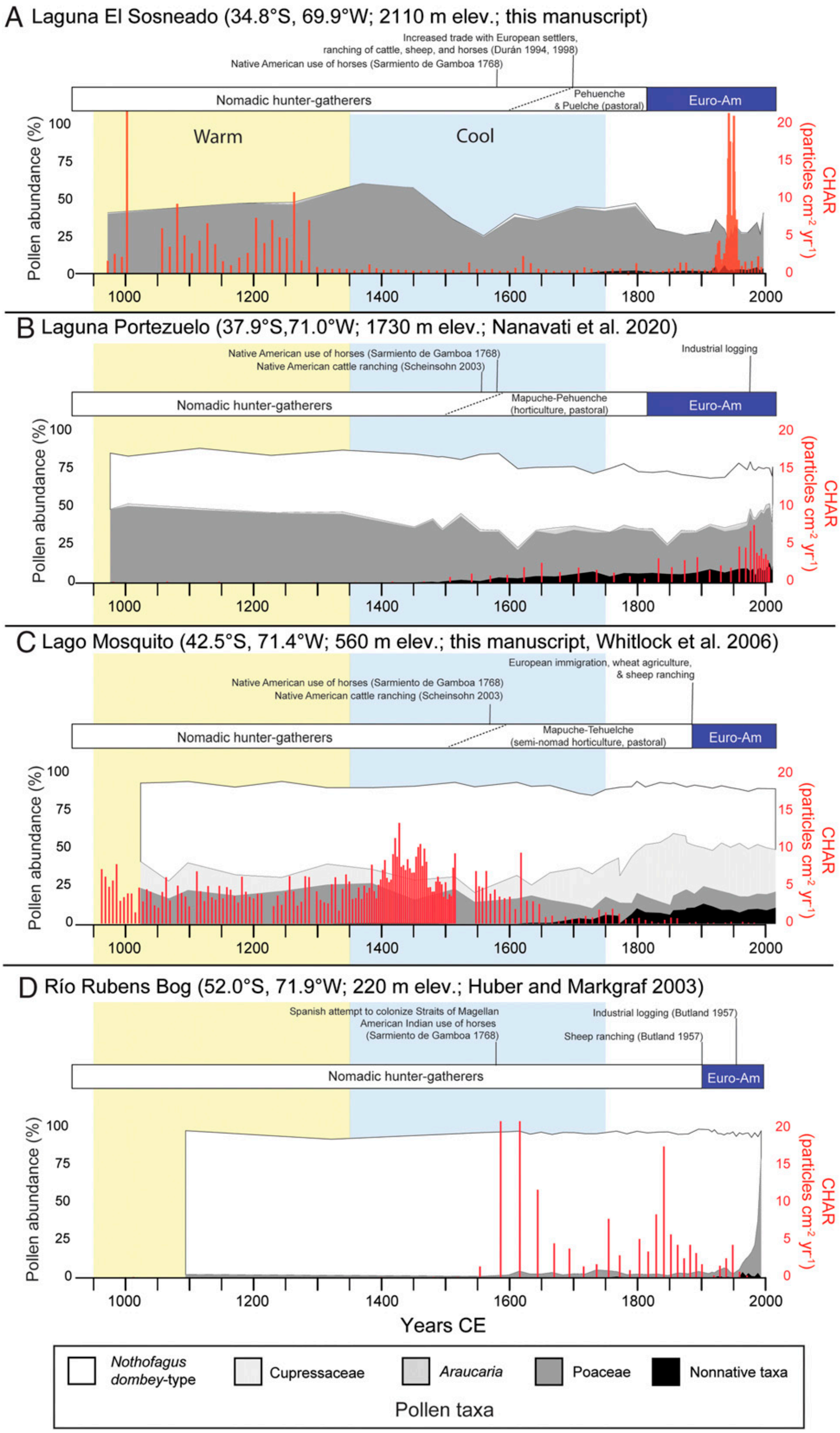

Fig. 3. The last 1,000 y of vegetation (percent pollen abundance; gray-scale silhouettes), fire (CHAR; red bars), climate (orange shading relates to MCA warming, blue shading relates to LIA cooling) (29–31), and human history from the paleoecological sites discussed in the text: (*A*) Laguna El Sosneado, (*B*) Laguna Portezuelo, (*C*) Lago Mosquito, and (*D*) Río Rubens Bog. Dashed, diagonal lines note cultural transitions that were gradual or dynamic.

Andes (58). CHAR levels were initially high during the MCA but decreased after ∼1460 CE (490 cal y BP) and reached null-to-low levels after 1650 CE (300 cal y BP) (Fig. 3*C*). The decline in fire in the 15th century occurred 400 y before widespread persecution of Native American populations by the Argentine and Chilean governments, arguing against a direct link between changes in fire activity and human conflict at that time (59). The recent expansion of *Austrocedrus* and reduction of fire, however, do coincide with the onset of LIA conditions, and a demographic transition from nomadic hunter-gatherers to less nomadic hunter-gatherer-horticulturalists, as Mapuche peoples immigrated east of the Andes and interacted with Tehuelche groups (45, 46). During the late 16th century, these groups adopted cattle pastoralism, horticulture, and used horses that were released by early European explorers, escaped from early ranches, or were taken from early European settlements (49–52). Nonnative pollen types (e.g., *R. acetosella*, *P. lanceolata*) increased at the expense of Poaceae after ∼1710 CE (240 cal y BP), well before local Euro-American settlement in the late 19th century. These findings suggest that the combination of a cooler LIA and change in land-use strategies led to a reduction of fire starting in the 15th century and an expansion of *Austrocedrus* in upland forests beginning in the 16th century. The near-absence of local fires in the last 200 y is consistent with Euro-American use of the valley for intensive livestock grazing and agriculture (9).

Río Rubens Bog. The pollen and charcoal records at Río Rubens Bog indicate that *Nothofagus* forest dominated the landscape with null-to-low fire activity since ∼5000 cal y BP (12). The data show little change in vegetation in the last 1,000 y until recent land use (Fig. 3*D*). The archaeological record near Río Rubens Bog indicates that dispersed and nomadic hunter-gatherers were present by ∼12,500 cal y BP. Although the populations increased after ∼8000 cal y BP, land-use strategies changed little until the arrival of Europeans, the introduction of nonnative species (e.g., horses and livestock), and the acquisition of new materials (e.g., glass and stoneware) (5, 36). Warm conditions during the MCA would have favored fuel flammability, but a lack of fires suggests that ignitions were limited. Charcoal data indicate that fire activity was initially high at ∼1590 to 1640 CE (360 to 310 cal y BP), which coincided with the first appearance of *R. acetosella* pollen, and again at 1790 and 1830 to 1840 CE (160 and 120 to 110 cal y BP). Early fires may have been set by the Native American groups to facilitate hunting (50, 51), but the fire periods also align with drought events around Río Rubens Bog (scPDSI values below −5) that may have facilitated fire spread (*SI Appendix*, Fig. S1*B*). Spanish colonies were established 200 km to the east along the Straits of Magellan by 1584 CE (366 cal y BP) (48, 50, 51), and *Rumex* may have been introduced through trade with Spanish encampments (17). Despite extensive sheep ranching by Euro-Americans at the end of the 19th century, pollen and charcoal data from Río Rubens Bog indicate little change in *Nothofagus* forest or fire activity until the mid-20th century, when forest clearance became widespread and fire activity declined (17, 48).

Conclusions

The vegetation and fire history at four sites spread across 18° of latitude along the eastern Andes in southern South America demonstrate the complex interactions between "natural" climate–vegetation–fire dynamics and changes in anthropogenic burning over the last 1,000 y. Humans provided an ignition source and altered the availability and flammability of fuels, at times muting or amplifying the effects of climate. For example, fire activity in the northern and southern sites was low at times when the climate was suitable for fire but lacked an ignition source (e.g., during the cold LIA at Laguna El Sosneado and the warm MCA at Río Rubens Bog). In contrast, the warm MCA at Laguna El Sosneado and Lago Mosquito was conducive to fires, set either by humans or infrequent lightning. The early appearance of nonnative plants and increases in fire activity at Laguna El Sosneado, Laguna Portezuelo, and Río Rubens Bog in the 16th century point to the indirect effects of European arrival to southern South America, namely the use of nonnative species by Native American groups. The direct effects of Euro-Americans on landscape development since the 19th century are evidenced by the expansion of shrublands and nonnative plants, as well as changes toward more (briefly at Laguna El Sosneado, Laguna Portezuelo, and Río Rubens) or less (Lago Mosquito) burning. Assessing the spatial extent of these human–environmental relationships in any one area will require additional paleoecological and archaeological studies.

Land-use strategies, including the use of fire, are driven by cultural as well as environmental factors. As Denevan (60) noted, human alteration of the environment is "not simply a process … in response to linear population growth and economic expansion. It is instead interrupted by periods of reversal and ecological rehabilitation as cultures collapse, populations decline, wars occur, and habitats are abandoned." Comparing high-resolution paleoenvironmental, archaeological, historical, and ethnographical records helps to clarify the ways that people have shaped past and present landscapes. An interdisciplinary approach makes it possible to: 1) document the long history of human–environment interactions in the Americas (e.g., ref. 61); 2) interpret how past land use amplified or reduced the impact of climate in shaping ecosystems (e.g., ref. 4); and 3) offer a plausible range of land-use scenarios under which cultures and ecosystems have evolved (e.g., ref. 2).

Recent studies (e.g., refs. 3 and 62) that assess past human influence on the environment at a global scale assume a nearly linear relationship between reconstructed population size and land use through time. Although these population-driven reconstructions of anthropogenic land cover provide useful hypotheses, the simplified population size–land use relationship misrepresents human influences at the local-to-regional scale, even in places where archaeological evidence is available for comparison. It also overlooks the influence of interannual-to-millennial scale climate variability in shaping vegetation and fire activity. In a similar manner, efforts to composite paleoecological information from multiple sites into a single record of change in regional-to-global vegetation or fire history tend to overestimate the role of climate while underestimating the influence of people in particular locations (e.g., refs. 63 and 64). Such composites often imply that climate is the primary driver of past fire activity, which is correct at broad scales, but not necessarily true at finer scales (10, 26, 65). Our study suggests that human's role in shaping past vegetation and fire activity in southern South America varied across an environmental gradient and was strongly influenced by the prevailing climate conditions.

Materials and Methods

Laguna El Sosneado, Laguna Portezuelo, Lago Mosquito, and Río Rubens Bog were selected for their well-constrained age-depth models, exceptionally high-resolution pollen and charcoal records for the last ∼1,000 y, and varying degrees of Native American and Euro-American land use (Fig. 1 and Table 1). Specific methods used in field work, laboratory analyses, and age-depth model development are provided in *SI Appendix*.

For this study, new cores were collected from Laguna El Sosneado with a modified square-rod Livingstone piston corer (66) and from Lago Mosquito with a Klein corer. Two cores were collected from Laguna El Sosneado: ES08A, from the *vega* (wetland) along the northern border of the lake, and ES08B, from the center of the lake. A Bayesian age-depth model for Laguna El Sosneado was developed separately for ES08A and ES08B. Ten radiocarbon dates from ES08A and two radiocarbon dates from ES08B were calibrated in 'Bacon' using the SHCal20 calibration curve (67, 68). The age-depth model for ES08B was further constrained by the presence of a tephra layer deposited during the 1932 CE Quizapu eruption (69), the initial rise in *Pinus* pollen (marking establishment of *Pinus* plantations, ∼1960 CE), and 2008 CE collection date (*SI Appendix*, Fig. S3 and Table S1). Similar methods were used to construct the Bayesian age-depth model for Lago Mosquito, based on four radiocarbon dates, the initial rise in *Pinus* pollen, and the 2016 CE collection date (*SI Appendix*, Fig. S4 and Table S2). Pollen and charcoal processing followed standard methods (70, 71).

Data Availability. The data have been deposited in the Neotoma Paleoecology Database (https://www.neotomadb.org/; Dataset IDs: 52656–52659).

ACKNOWLEDGMENTS. Drs. Gustavo Villarosa and Valeria Outes made available the Laguna Portezuelo cores, and Drs. Virginia Iglesias and Christopher Schiller assisted with Laguna El Sosneado laboratory work. This material is based upon work supported by a Consejo Nacional de Investigaciones Científicas y Técnicas de Argentina Postgraduate Fellowship (to D.N.); National Science Foundation through Social, Behavioral, and Economic Sciences Postdoctoral Research Fellowship 2004941 (to W.N.); and National Science Foundation Grant 1461590 (to C.W.).

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