Southern Annular Mode Drives Multicentury Wildfire Activity in Southern South America

Andrés Holz
Portland State University, andres.holz@pdx.edu

Juan Paritsis
Universidad Nacional del Comahue

Ignacio A. Mundo
Universidad Nacional de Cuyo UNCUyO - CE Prospectiva -Argentina

Thomas T. Veblen
University of Colorado Boulder

Thomas Kitzberger
Universidad Nacional del Comahue

See next page for additional authors

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Authors
Andrés Holz, Juan Paritsis, Ignacio A. Mundo, Thomas T. Veblen, Thomas Kitzberger, Grant J. Williamson, Ezequiel Aráoz, Carlos Bustos-Schindler, Mauro E. González, H. Ricardo Grau, and Juan M. Quezada

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Southern Annular Mode drives multicentury wildfire activity in southern South America

Andrés Holz\textsuperscript{a,} \textsuperscript{b}, Juan Paritis\textsuperscript{c}, Ignacio A. Mundo\textsuperscript{d,} \textsuperscript{e}, Thomas T. Veblen\textsuperscript{f}, Thomas Kitzberger\textsuperscript{g}, Grant J. Williamson\textsuperscript{h}, Ezequiel Aráoz\textsuperscript{i}, Carlos Bustos-Schindler\textsuperscript{j}, Mauro E. González\textsuperscript{k}, H. Ricardo Grau\textsuperscript{l}, and Juan M. Quezada\textsuperscript{m}

\textsuperscript{a}Department of Geography, Portland State University, Portland, OR 97207; \textsuperscript{b}Laboratorio Ecológico, Instituto de Investigaciones en Biodiversidad y Medioambiente, Consejo Nacional de Investigaciones Científicas y Técnicas, Universidad Nacional del Comahue, 8400 Bariloche, Argentina; \textsuperscript{c}Laboratorio de Dendroclimatología e Historia Ambiental, Instituto Argentino de Nivología, Glaciología y Ciencias Ambientales, El Centro Científico Tecnológico, Consejo Nacional de Investigaciones Científicas y Técnicas, M5502RIA Mendoza, Argentina; \textsuperscript{d}Facultad de Ciencias Exactas y Naturales, Universidad Nacional de Cuyo, M5502JMA Mendoza, Argentina; \textsuperscript{e}Department of Geography, University of Colorado, Boulder, CO 80309; \textsuperscript{f}School of Biological Sciences, University of Tasmania, Hobart, TAS 7001, Australia; \textsuperscript{g}Instituto de Ecología Regional, Consejo Nacional de Investigaciones Científicas y Técnicas, Universidad Nacional de Tucumán, 4172 Yerba Buena, Argentina; \textsuperscript{h}Instituto de Conservación, Biodiversidad y Territorio, Facultad de Ciencias Forestales y Recursos Naturales, Instituto de Silvicultura, Universidad Austral de Chile, Valdivia, Chile; \textsuperscript{i}Center for Climate and Resilience Research (CR2), Santiago, Chile; \textsuperscript{j}Facultad de Ciencias Naturales e Instituto Miguel Lillo, Universidad Nacional de Tucumán, 4000 San Miguel de Tucumán, Argentina; and \textsuperscript{m}Facultad de Ciencias Forestales, Universidad Nacional de Misiones, Eldorado, 3380 Misiones, Argentina

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The Southern Annular Mode (SAM) is the main driver of climate variability at mid to high latitudes in the Southern Hemisphere, affecting wildfire activity, which in turn pollutes the air and contributes to human health problems and mortality, and potentially provides strong feedback to the climate system through emissions and land cover changes. Here we report the largest Southern Hemisphere network of annually resolved tree ring fire histories, consisting of 1,767 fire-scarred trees from 97 sites (from 22°S to 54°S) in southern South America (SAS), to quantify the coupling of SAM and regional wildfire variability using recently created multicentury proxy indices of SAM for the years 1531–2010 AD. We show that at interannual time scales, as well as at multidecadal time scales across 37–54°S, latitudinal gradient elevated wildfire activity is synchronous with positive phases of the SAM over the years 1665–1995. Positive phases of the SAM are associated primarily with warm conditions in these biomass-rich forests, in which widespread fire activity depends on fuel desiccation. Climate modeling studies indicate that greenhouse gases will force SAM into its positive phase even if stratospheric ozone returns to normal levels, so that climate conditions conducive to widespread fire activity in SAS will continue throughout the 21st century.

Significance

Fire is a key ecological process affecting ecosystem services, driven primarily by variations in fuel amount and condition, ignition patterns, and climate. In the Southern Hemisphere, current warming conditions are linked to the upward trend in the Southern Annular Mode (SAM) due to ozone depletion. Here we use tree ring fire scar data obtained from diverse biomes ranging from subtropical dry woodlands to sub-Antarctic rainforests to assess the effect of the SAM on regional fire activity over the past several centuries. Our findings reveal a tight coupling between fire activity and the SAM at all temporal scales and in all biomes, with increased wildfire synchrony and activity during the 20th century compared with previous centuries.


The authors declare no conflict of interest.

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Data deposition: The tree-ring fire scar data reported in this paper have been deposited in the International Tree-Ring Data Bank (ITRDB), https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring.

1To whom correspondence should be addressed. Email: andres.holz@pdx.edu.

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present) for specific forest types based on tree ring fire histories (7, 18). However, we lack a comprehensive understanding of the SAM’s influence on fire activity over multiple centuries and at a broad latitudinal extent of forest ecosystems in SSA. We hypothesize that in biomass-rich temperate forests extending from ~37° to 55° S in SSA, the SAM promotes fire primarily by enhancing warm spring-summer conditions, which in turn desiccate fuels. Here we used 4,587 annually resolved fire scar dates from 1,767 fire-scarred trees collected at 97 sites (the largest paleofire record yet assembled for the Southern Hemisphere) to reconstruct regional fire records for eight regions that extend from subtropical to sub-Antarctic latitudes in SSA and span the period 990–2010 AD (Fig. 2 and SI Appendix, Fig. S1 and Table S1). From these fire scar dates, we developed indices of regional- and subcontinental-scale fire activity and synchrony to examine relationships between the SAM and local and regional climate parameters across SSA at
multiple time scales. Our rationale is that at the regional and subcontinental scales, high synchrony indicates a strong influence of climatic variations on fire (19), and that overall high fire activity could have a strong association with climate variability (19–21) as well as with changes in ignition owing to either natural (22) or human (23–25) causes.

We used a recently developed proxy reconstruction of summer (December–February) SAM (9, 26) to examine the relation of fire activity to variability in the SAM (Methods). This SAM reconstruction has proven useful in explaining tree growth variability over the 1984–2010 period (3).

The collective fire history of all study regions’ chronologies south of 37°S (combined (minimum of two trees and 10% of recorder trees per site) shows a rapid decline from early in the record (1400s) to the 1700s, when fire activity increased gradually (SI Appendix, Fig. S1). Starting in the 1850s, fire activity increased very abruptly, and large fire years occurred roughly every 15–20 y until the 1920–1940s, when fire activity dropped. Starting in the 1960s, fire activity ramped up again and has continued to the present day (SI Appendix, Fig. S1).

The temporal pattern of the collective fire history of all regions is similar to the standardized synthesis of all charcoal records located south of 30° S in western South America (29). The post-1960s increases in fire activity have been driven primarily by fire activity at mid and high latitudes on the west side of the Andes (Fig. 2A), where wildfires on the eastern Andean slope show the effects of active fire suppression since the 1930s–40s (Fig. 2A). The subcontinental-scale fire indices indicate that both the magnitude of fire activity (SCFA) and fire synchrony (SCFS) among regions have fluctuated over time and that in general there is no clear relationship between these two indices (Fig. 2E and F). In contrast to the SCFA index, the amplitude in the SCFS index has increased over time, with higher maximum values and lower minimum values in the latter part of the analyzed period (1738–1932) compared with early in the record.

Relatively weak but significant correlations were found for both subcontinental fire indices (SCFA: $r = 0.2, P < 0.01$; SCFS: $r = 0.18, P < 0.01$) and the SAM during the 1738–1932 period (Table 1). Series were prewhitened to remove autocorrelation, and the trend-free records were filtered with a 15-y spline to match the main spectra of the SCFA (SI Appendix, Fig. S5). Likewise, similar low-frequency variability patterns were shared between the temperature...
and SCFA indices \( r = 0.12, P < 0.01 \) and between the precipitation and SCFS indices \( r = 0.24, P < 0.01 \) (Table 1).

The patterns of wavelet coherence between the SCFA and both the SAM and temperature indices show numerous shorter (ca. four 2–8 y) and longer (ca. two 10–18 y) periods with either in-phase and/or delayed in-phase coherence throughout the recording period (Fig. 3A and B and SI Appendix, Text ST1). Similarly, the SCFS and SAM indices share similar common numerous short (ca. 4–8 y) and a few longer (ca. 8–12-y) periods with either in-phase and/or delayed in-phase coherence (Fig. 3D). Some of the short period coherence might reflect the linkage of fire and the climatic parameters to ENSO variability documented in previous studies (5–7, 30, 31); however, the goal of the present analysis was to identify the SAM signal in the coherence patterns. Only decadal-scale in-phase and/or delayed in-phase coherence (ca. 28–34 y) is shared between SCFS and temperature (Fig. 3E). The precipitation index and both fire indices share mostly antiphase or delayed antiphase coherence (i.e., drought and fire), with common numerous short (ca. 1–8 y) and fewer longer (ca. 8–10 y) periods (Fig. 3C and F). Precipitation also shares a few common in-phase and/or delayed in-phase coherence of longer (ca. 10–16 y) periods with the SCFS (Fig. 3F).

Overall, wavelet coherence analyses on the SCFA also show a predominant role of drought in the first third of the record (i.e., 1738–1825), with the SAM and temperature indices increasing in relevance over the remaining record (Fig. 3A–C). Similarly, an increase in coherence between the precipitation and SCFS indices is also observed from the 1780s to 1930s (Fig. 3F), but no obvious change in coherence over time is noted between the SCFS and either the SAM or temperature index (Fig. 3D and E).

The foregoing results indicate that at the subcontinental-scale, large wildfire years (SCFA) were driven primarily by warm conditions teleconnected with a positive SAM during 1738–1932. Some years of high synchrony in subcontinental fire activity are linked to reduced rainfall. In both cases, our rationale in interpreting these results is that in SSA [and elsewhere (19, 20, 32)], large fire years in cool and/or wet forests with abundant fuels and a short fire season have been commonly associated with periods of warm and dry conditions that reduce fuel moisture and favor fire activity. It was suggested that the association between high fire synchrony and above-average precipitation reflects the spread of fires that began in fuel-limited grasslands adjacent to the core areas sampled for fire scars, where previous research had shown a lagged association of fire and fine fuel-enhancing moister conditions (5, 33). This interpretation is consistent with the lagged association of fire with above-average moisture availability in grassland habitats throughout SSA based on modern climate-fire analyses using instrumental climate records and observations of annual area burned.

The peaks in fire activity in the mid-1800s and early 1900s have been linked to coincident increases in human-set fires and climate variability in some of our study regions (6, 34, 35). While increases in fire frequencies in association with the increased presence of

### Table 1. Pearson correlation values of 15-y smoothed time series (\( z \)-scores) of climate and fire (SCFA and SCFS) over the 1738–1932 period \( (n = 194) \)

<table>
<thead>
<tr>
<th>Series</th>
<th>( r ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCFA vs. SAM</td>
<td>0.20***</td>
</tr>
<tr>
<td>SCFA vs. temperature</td>
<td>0.12*</td>
</tr>
<tr>
<td>SCFA vs. precipitation</td>
<td>-0.09</td>
</tr>
<tr>
<td>SCFS vs. SAM</td>
<td>0.18**</td>
</tr>
<tr>
<td>SCFS vs. temperature</td>
<td>-0.05</td>
</tr>
<tr>
<td>SCFA vs. precipitation</td>
<td>0.24***</td>
</tr>
<tr>
<td>SCFA vs. SCFS</td>
<td>0.07</td>
</tr>
</tbody>
</table>

All reconstructions were filtered with a 15-y spline to emphasize the correlations among the lower frequency of all records. All time series were detrended. Pearson correlation coefficients were calculated from prewhitened series using the trend-free prewhitening procedure in the zyp R package. The subcontinental fire indices were built using a constant number of fire recording sites over the 1738–1932 period. *\( P < 0.05 \); **\( P < 0.01 \); ***\( P < 0.001 \).
indigenous and modern humans are detectable in specific habitats, periods of synchronous widespread fire documented at annual resolution in tree ring studies and at multidecadal resolution in sedimentary charcoal studies have been more strongly linked to climatic variability (4, 6, 34). Human amplification or dampening of climate-induced trends in wildfire activity would not have been synchronous across the six study areas, given different time periods of migrations of indigenous populations and colonization by populations of European origin until the 1930s–1940s, when fire records in some regions clearly reflect fire exclusion (e.g., ref. 7), but records in other regions reflect increased burning by modern humans (34). Thus, we use 1932 as a cutoff to reduce the impact of modern changes in human ignition (Fig. 2 A and F and Methods) while acknowledging that in some regions, pre-1932 human amplification and/or changes in lightning activity (1, 36) might have affected both subcontinental-scale indices (SCFA and SCFS).

Conclusions and Implications

In SSA, wildfire activity is strongly associated with warm conditions teleconnected with positive SAM at multiple time scales both directly and in combination with a long-lasting drought that was amplified by concurrent positive a SAM at the intraregional scale (mainly north of 44°S) both directly and in combination with a positive SAM at the intercontinental scale (Fig. 2A and F). This dataset consists of ~37–54% of only that period as defined by the boxes in the map shown in Fig. 2A. The atmospheric greenhouse gases are also expected to force more frequent extreme El Niño events (38), which have been shown to be strongly associated with years of large wildfire activity in SSA (mainly north of 44°S) both directly and in combination with a positive SAM at the intraregional scale (SI Appendix, Tables S2 and S4). During the 2016–17 fire season, more than 500,000 hectares affected in the zone between ~29°S and 40°S (~3–5% of only that latitudinal zone) were burned in central and southern Chile, driven by a long-lasting drought that was amplified by concurrent positive SAM and ENSO conditions. While wildfire activity is expected to continue to reflect interannual variability related to ENSO, the continued dominance of the SAM as the primary driver of extratropical climate variability in the Southern Hemisphere (11, 37) portends increased wildfire activity in SSA for the 21st century.

Methods

Study Sites and Species. Tree ring fire scar records were obtained from the International MultiproxyPaleofire Database (IMPD), and from published and unpublished sources (SI Appendix, Table S1). This dataset consists of 1,767 fire-scarred trees from 97 sites in SSA extending from northwestern Argentina to southern Patagonia, which were grouped into eight regions of homogeneous climate variability (Fig. 2A) following ref. 3. Included ecosystems range from relatively dry woodlands and forests to mesic and rain forests and bogs.

Indices. We created regional- and subcontinental-scale indices of years of fire activity to highlight and test for changes at interannual and decadal scales. Annual indices of fire occurrence (i.e., fire index) were calculated for each of the 97 sites by dividing the number of fire-scarred trees per year (with a minimum of two) by the number of trees potentially recording fire in that year, as described previously (24, 39). The start and end dates for each site fire index were determined using a minimum of four samples capable of recording fire. A region-wide fire index (for each of our eight regions) was then calculated as the sum of the site indices per year divided by the number of sites recording fire in that year (SI Appendix, Table S3). The SCFA was then calculated as the sum of the regional fire indices per year divided by the number of regions recording fire in that year (Fig. 2F). For the SCFS, in a manner of a previously described method (19), annual fire synchrony between paired regions was identified by calculating the number of fire years recorded in both regions divided by the number of fire years recorded in either region over a centered 15-y period. This procedure was repeated in the 15 possible combinations of pairs of the six regions (the records for the two northernmost regions were too short and thus were not included) and summed as total fire synchrony, or SCFS (Fig. 2E).

A cutoff date of 1738 was chosen for all statistical analyses (see below) to ensure a minimum sample of recording sites (n = 8; >10%), a sufficient and commonly used percentage to characterize fire regimes in SSA (6, 7, 18, 30, 31). In addition, the time period of analysis ends in 1932, when both the earliest known effective fire suppression in SSA is evident in the fire records of the Rio Negro and Neuquén regions, and a pulse of fire activity is initiated in the 1940s in the Aysén region associated with modern frontier activity and road construction (Fig. 2A and SI Appendix, Tables S1 and S3).

The annually resolved reconstructions of the SAM (Fig. 2B), the Southern Hemisphere temperature index (28) (Fig. 2C), and the SAS precipitation index (27) (Fig. 2D) were obtained from the paleoclimatology datasets of the National Centers for Environmental Information (https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/climate-reconstruction). The SAM reconstruction was developed from tree ring records, and the temperature and precipitation reconstruction developed from lake sediments, ice cores, documentary, coral and speleothem records (SI Appendix, Text S1). Several SAM reconstructions have been developed (13, 26), all of which share some of the same proxies (e.g., tree ring chronologies) and thus are not independent reconstructions. We chose to use the SAM (based on the Marshall Index (9)) reconstruction because (i) the instrumental index used to build the SAM reconstruction is based on sea-level atmospheric pressure records from stations located between 40°S and 65°S, rather than on reanalysis data (SAM NCEP-NCAR), which has been shown to magnify the increase in the SAM signal over the past decades (9); (ii) the region (40–65°S) used to build the index is more relevant to our study area than locations of proxies used in other reconstructions (13, 26); (iii) in the study areas, the summer season (i.e., December–February) of the SAM reconstruction is strongly correlated with fire occurrence, which is the key driver of fuel desiccation (13); and (iv) analyses based on an alternative SAM reconstruction (SAM NCEP-NCAR) were very similar (data not shown).

Seasonal subsets of monthly gridded precipitation and temperature (0.5 × 0.5 degrees; Climate Research Unit TS3.22, 1901–2013) data used to conduct bootstrapped correlation functions (see below) were derived for each study region as defined by the boxes in the map shown in Fig. 2A. The instrumental index of the SAM used was the Marshall’s instrumental index (9), which is based on selected station pressure records for 40–65°S over the period 1957–2013. This instrumental SAM index is strongly correlated with tree growth in SSA (26).

Statistical Analyses. We performed three analyses to examine the spatio-temporal associations between wildfire activity in SSA and variability in the SAM, precipitation, and temperature index reconstructions. First, at the regional scale, we determined interannual-scale departures from long-term mean SAM during periods of widespread fire and nonfire years in each of the study regions using superposed epoch analysis (SEA) (33) in the dplR package (40) in R (41) (SI Appendix, Fig. S2). For the SEA, years of widespread fire within each study area were defined as years when ≥2 trees were scarred, with a minimum of four trees capable of recording fire per site at ≥10% of sites (i.e., region-wide fire index for each of our eight regions). A 5-y window of mean SAM was centered on years of widespread (and no fire scars; SI Appendix, Fig. S3) fires for each of the study regions. Significance levels of the departures from the long-term mean were determined from bootstrapped 95% confidence intervals estimated from 10,000 Monte Carlo simulations (42). Modern teleconnections of the instrumental SAM index to local climate variability (mechanically responsible for variability in wildfire activity) were examined with bootstrapped correlation functions using the bootRes package (43) relating the observed SAM and seasonal gridded climate data for each of the eight study regions (as defined by boxes in the map shown in Fig. 2A and SI Appendix, Fig. S4). The results of this first analysis were compared with those obtained from modern relationships (significant correlation; P < 0.05) between seasonal observations of both climate parameters and SAM and annual area burned in woody vegetation during the 1984–2008 period (results from ref. 3 and SI Appendix, Table S4).

Secondly, at the subcontinental scale, wavelet coherence was used to test whether fire activity and climatic parameters had similar periodicities, using the
Biwavelet package in R. Wavelet coherence, which identifies regions in time and space in which two variables covary, is especially suitable for the analysis of non-Gaussian time series, including climate and fire data (32). The Morlet continuous wavelet transform was applied, and the data were padded with 0s at each end to reduce wraparound effects (44). We plotted phase arrows indicating the direction of the correlation only when the wavelet coherence power exceeded the 95th percentile (Fig. 3). Although we found no difference in the coherence patterns compared with analyses conducted using standardized (z-scores) time series alone or standardized and detrended time series, before conducting wavelet analyses, we standardized time series (to z-scores) and removed trends and serial autocorrelation using autocorrelation functions and autoregressive moving average models (trend-free, prewhitened) using the Yue-Pilon method (45) in the zyp package in R.

Third, and also at the subcontinental scale, we used the Spearman correlation function to test the long-term (decadal-scale) relationships among the reconstructed SAM, the climate parameters, and both subcontinental fire indices (SCFA and SCFS) (Table 1). To highlight decadal-scale variability in climate-fire relationships, we used singular spectral analysis to determine the dominant periods at which variance occurred in the SCFA index (46); specifically, we used the multitaper method (47) to identify a window of 15 y as a cycle that explains significant proportions of variance in the SCFA over the 1738–1932 period (SI Appendix, Fig. S5). We used the 15-y window to construct a smoothed SCFA and the climate time series, as well as to build the SCFS. To ensure that the correlation coefficients computed in this third step were not influenced by changes over time in the sample depth (i.e., number of trees, sites, and regions recording fire), we computed correlation coefficients using a constant sample depth (10% of sites with fire-scarred trees) over time over the 1738–1932 period; that is, once the 10% criterion was achieved, new fire dates from recorder trees starting after 1738 were not added into the regional chronologies.

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