Author/s:
Mariani, M;Fletcher, MS

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TITLE: The Southern Annular Mode determines inter-annual and centennial-scale fire activity in temperate southwest Tasmania, Australia.

Mariani, Michela[1*]

mmariani@student.unimelb.edu.au

Fletcher, Michael-Shawn[1]

michael.fletcher@unimelb.edu.au

[1]School of Geography, The University of Melbourne, 221 Bouverie Street, Carlton, Australia, 3053.

*corresponding author

ABSTRACT

Southern Annular Mode (SAM) is the primary mode of atmospheric variability in the Southern Hemisphere. While it is well established that the current anthropogenic-driven trend in SAM is responsible for decreased rainfall in southern Australia, its role in driving fire regimes in this region has not been explored. We examined the connection between fire activity and SAM in southwest Tasmania, which lies in the latitudinal band of strongest correlation between SAM and rainfall in the Southern Hemisphere. We reveal that fire activity during a fire season is significantly correlated with the phase of SAM in the preceding year using Superposed Epoch Analysis. We then synthesised new 14 charcoal records from southwest Tasmania spanning the last 1000 years, revealing a tight coupling between fire activity and SAM at centennial timescales, observing a multi-century increase in fire activity over the last 500 years and a spike in fire activity in the 21st century in response to natural and anthropogenic SAM trends.

INTRODUCTION

[1] Fire a key Earth System Process, driving global ecosystem patterns and processes, determining global vegetation distribution [*Bond et al.,* 2005], modulating the carbon cycle [*Liu et al.,* 2015] and influencing the climate system [*Bowman et al.,* 2009]. Despite the clear importance of fire, the drivers of fire activity through time are poorly understood in many regions on Earth. A case-in-point is the range of explanations invoked to account for the increase in fire activity in temperate forest ecosystems across the globe over recent decades [*Holz and Veblen*, 2011; *Meyn et al.*, 2007; *Parisien and Moritz*, 2009, *Moritz et al.*, 2012], which include climate change, human ignitions, land-use change and/or altered vegetation structure and patterns [*McWethy et al.*, 2013]. Fire activity over the last few centuries in the temperate forests of Patagonia, for example, has recently been linked to hydro-climatic variability associated with the Southern Annular Mode (SAM) [*Holz and Veblen*, 2011]. SAM is the leading mode of Southern Hemisphere climatic variability [*Fogt et al.*, 2009], prompting the question of whether the relationship between SAM and fire in temperate Patagonia holds across the entire Southern Hemisphere or whether it is a more localized southern South American phenomenon. In this paper, we (1) explore the relationship between SAM and fire occurrence in southwest Tasmania, Australia, a temperate region in which rainfall and temperature variability are controlled by SAM; and (2) test whether the persistent trend toward a positive SAM state over the last 500 years, particularly over the 21st century [*Abram et al.*, 2014] has influenced fire activity in this temperate region.

[2] SAM describes the north–south movement of the Southern Westerly Wind belt (SWW), a zonally symmetric climate feature that encircles Antarctica and which controls rainfall and

temperature variability across the extra-tropics of the entire Southern Hemisphere [*Garreaud*, 2007; *Gillett et al.*, 2006; *Hill et al.*, 2009]. In the positive phase of SAM, the SWW contract poleward facilitating the development of high pressure systems over southern Australia and Tasmania, resulting in a decrease in rainfall. Conversely, the negative phase of SAM sees an expansion of SWW towards the equator, bringing low pressure systems and their associated storm tracks over Southern Australia and Tasmania, resulting in increased rainfall [*Fogt et al., 2009*; *Garreaud et al.,* 2009; *Hill et al.,* 2009; *Risbey et al.,* 2009; *Abram et al.,* 2014] (Figure 1). Inter-annual positive anomalies of SAM are associated with higher temperatures and lower precipitation across the Southern Hemisphere [*Gillett et al.*, 2006; *Hendon et al.*, 2007; *Hill et al.*, 2009]. Importantly, the last ~60 years is characterised by a trend toward extreme positive SAM in response to ozone depletion [*Thompson and Solomon, 2002; Marshall, 2003; Perlwitz et al.*, 2008] that is associated with warmer and drier conditions across the southern extra-tropics [*Smith and Reynolds*, 2005; *Fogt et al.*, 2009]. Moreover, this trend is embedded within a longer centennial-scale trend toward positive SAM occurring over the last 500 years [*Abram et al.*, 2014] and it is unknown what, if any, impact this has had over Southern Hemisphere fire activity.

[3] Fire occurrence and spread is determined by the confluence of sufficient fuel, an ignition source and suitable weather: the fire-triangle [*Krawchuk et al.*, 2009]. In areas of high biomass (read: abundant fuel), such as southwest Tasmania, fire occurrence through time is modulated by fuel moisture (i.e. climate) and ignitions (lightning and humans) [*Cochrane*, 2003; *Pausas & Ribeiro*, 2013; *Bradstock*, 2010; *McWethy et al.*, 2013]. Humans have actively used fire to modify the Tasmanian environment for more than 40,000 years

[*Cosgrove*, 1999; *Fletcher and Thomas*, 2010; *Jones*, 1969] and, along with lightning strike (which account for less than 0.1% of ignitions [*Bowman and Brown*, 1986], the constant source of ignition in this landscape effectively isolates climate variability as the principal factor modulating the occurrence of fire through time. Fires in Tasmania are driven by seasonal, inter-annual and decadal variations in temperature and rainfall: i.e. fires occur in response to hot and dry conditions [*Nicholls & Lucas,* 2007]. Rainfall in southwest Tasmania is derived entirely from the SWW and inter-annual variations in rainfall are controlled by SAM (Figure 1). We posit, then, that if fire activity in this landscape is modulated by climate, inter-annual fire activity should be correlated with SAM. Further, if this relationship exists, we hypothesise that the persistent 21st century trend toward extreme positive SAM phase will have increased the risk of fire in this landscape, placing highly fire sensitive endemic ecosystems in this region at risk of extinction.

[4] Southwest Tasmania is a topographically complex landscape that hosts a number of extremely fire sensitive endemic vegetation systems that have suffered substantial fire-driven range contraction throughout the Holocene [*Fletcher et al.*, 2014; *Fletcher et al.*, 2013] and since European colonisation [*Cullen*, 1987; *Holz et al.*, 2014]. Indeed, the distribution of rainforest in this region is, like much of the highly flammable Australian continent, restricted to fire refugia that are determined principally by topography and non-linear feedbacks between vegetation type and flammability [*Jackson*, 1968; *Bowman*, 2000; *Wood et al.*, 2011]. Not only does the current SAM trend pose a potentially significant threat to the security of the remaining pockets of fire-sensitive ecosystems via a shortening of the fire return interval, the potential reduction in rainfall associated with this trend in southern

Australia and Tasmania [*Fyfe and Saenko,* 2006; *Miller et al.*, 2006] creates increasingly inhospitable climatic conditions for plant growth and recovery. This threefold impact of current climate trends, termed “interval squeeze” [*Enright et al.*, 2015], threatens fire-sensitive ecosystems with extinction. Thus, it is critical that we attempt to understand the role that climate has in driving long-term fire activity, so that realistic management options for our natural systems can be explored.

[5] In this paper, we explore the relationship between climate and fire occurrence in southwest Tasmania, testing whether the reported relationship between SAM and fire activity in Patagonia is also manifest in Tasmania. We then draw on a database of palaeofire records from this region spanning the last 1000 years to test for a link between SAM and palaeofire activity in southwest Tasmania at centennial scales. We specifically ask: (1) does SAM driven climate variability control contemporary fire activity in southwest Tasmania? (2) Does centennial-scale SAM variability control longer-term fire activity in southwest Tasmania? (3) Is there an upward spike in fire activity related to the current positive SAM trend driven by ozone depletion?

METHODS

[6] To identify the principal driver of rainfall in our study region we created a correlation map between annual rainfall anomalies and all of the main climate indices identified as important drivers of rainfall anomalies in southern Australia (SAM, the El Niño Southern Oscillation [ENSO], the Indian Ocean Dipole [IOD] and the Pacific Decadal Oscillation [PDO]). We calculated correlation coefficients (*r*) between annual rainfall anomalies during the period 1961-1990 for 220 meteorological stations (data from Australian Bureau of Meteorology – BOM) and the annual climate indices for the Marshall (2003) SAM index (British Antarctic Survey), ENSO (SOI Index from NOAA), IOD (DMI Index, http://www.jamstec.go.jp/frcgc/research/d1/iod/HTML/Dipole%20Mode%20Index.html) and PDO (Index from NOAA) (Figure 1 and Figure S1 in the Supporting Information). Climate modes operate at scales ranging from seasonal to centennial and we selected the average annual values of the climate indices for this analysis. Rainfall anomalies are the differences between the total precipitation of each year and the average total precipitation of the 30-year baseline period. The *r* values from the stations have been spatially interpolated using the Universal Kriging method in ArcMap 9.3 [ESRI - Environmental Systems Resource Institute, 2009, Redlands, California]. Coordinates system is GDA 1994 Zone 55 and the grid resolution is 1.8 x 1.8 km. The results of this analysis clearly reveal SAM as the key driver of rainfall variability in SW Tasmania over the analysis period (Figure S1), with all other indices displaying little or no explanatory power for rainfall anomaly in this area. Thus, we focus on SAM for the remainder of this paper. We restrict our analysis of fire occurrence to what we deem as the "SAM zone", identified as the area with an *r* correlation coefficient > 0.3.

[7] Fire occurrence data for the SAM zone were obtained from the Land Information System Tasmania (theList, Government of Tasmania). Since the total number of fires before the 1990's is very low, likely due to the remoteness of this area precluding accurate fire detection at that time, only contiguous years (considered as fire ignition seasons – late spring/early autumn) with a total number of fires >25 across the island have been chosen, i.e. the period between fire-seasons of 1991/1992 and 2013/2014. While this represents a relatively short period for correlation, we feel that this dataset represents the best current dataset for testing the important questions tackled by this paper, which can be crucial in fire activity forecasting and management. This need is clear, given the current (2016) fires devastating that are sweeping across SW Tasmania and destroying fire-sensitive these ecosystems following the second strongest dry SAM year on record. Figure 1 presents the location of all fires used in our analysis plotted with the spatial correlation between fire-season SAM and rainfall anomalies. We include both human-caused and natural fires in the analyses, with the exception of deliberate management fires (i.e. prescribed/management fires).

[8] To identify a relationship between the annual SAM index and fire occurrence in the SAM zone, we performed Superposed Epoch Analysis (SEA) analysis in R v.3.0.3. This analysis allows assessing the significance of the departure from the mean for a given set of key event years (e.g. fire years) and lagged years [*Lough and Fritts*, 1987]. The fire occurrence data for 'fire seasons' (number of fires and area burnt) and the SAM index were converted to z-scores (using the entire series mean) prior to analysis and significant deviations from the mean were

used to identify “fire years” and “non-fire years”. Fire seasons span the period between December and March and include ca. 80% of fires occurring in any 12 month period. The unique landscape-scale vegetation mosaic in SW Tasmania, which juxtaposes pyrophobic (fire-retarding) and pyrogenic (fire-promoting) vegetation types, exerts a major influence over the spread and extent of fires, thus, we hypothesised that changes in the number of fires will more accurately reflect changes in the broad-scale drivers of fire activity in this landscape than the more traditionally employed area burnt metric.

[9] For our last 1000 year palaeofire analysis, we synthesised new sedimentary charcoal records analysed by our research team and located within the “SAM zone” identified in our climate analysis (Figure 1 and S2). Chronology of the charcoal records is based on radiocarbon and Lead-210 assays (Table S1), with age-depth modeling performed using Clam v2.1 [*Blaauw*, 2010]. A charcoal composite curve for all 14 sites was performed using the Paleofire package in R [*Blarquez et al.*, 2014]. A 50 year interval for this analysis was chosen, since it represents the best achievable resolution in order to include the majority of records for the entire reconstruction period. The full list of the sites used in the palaeofire analysis is shown in Table S1, along with the charcoal records for the last 1000 years (Figure S2).

RESULTS

[10] The spatial climate correlation analysis shows a distinct pattern of correlation between SAM and rainfall anomalies across the island of Tasmania: a strong SAM-rainfall correlation in the southwest and no correlation in the north-east and east (Figure 1). A total of 368 fires (accidental human-ignited and naturally ignited) were identified in the SAM zone during the period 1992-2014 (Figure 1). The SEA reveals a statistically significant (p value <0.05) positive annual SAM departure occurring in the year preceding a fire season (Figure 3a). To support this result, we show that "non-fire years" (fire seasons with an anomalously low fire occurrence) correspond to a significant (p value <0.05) negative departure in SAM (Figure 3b). Area burnt (both "fire-years" and "non-fire years") did not show any relationship with the annual SAM Index (Figures 3c and 3d). The palaeofire composite analysis of our new dataset of 14 southwest Tasmanian charcoal records spanning the last 1000 years shows initially high fire activity around 1000 CE, a sharp decline to minimum values at 1400 CE and a persistent increase toward the present, interrupted by a plateau between 1600-1800 CE and finally by a precipitous increase from 1800 CE to the present (Figure 4).

DISCUSSION

[11] Our analysis reveals, for the first time, that the phase of SAM preceding a fire season in SW Tasmania determines inter-annual fire activity in this landscape (Figure 2 and 3). Further, the results confirm our hypothesis that trends in the number of fires in the landscape of SW Tasmania are more reflective of changes in the climatic drivers governing fire activity than the area burnt. This finding is entirely consistent with the dominant influence that the fine-scale mosaic of juxtaposed pyrophobic and pyrogenic vegetation types has over the spread and extent of fires in this region [Jackson, 1968; Wood and Bowman., 2011; Wood and Bowman, 2012]. The stark contrast in fuel moisture content, flammability and fire-sensitivity of vegetation types in this region [Pyrke and Marsden-Smedley, 2005] dictates that the relationship between the area burnt and climate is unlikely to be linear. Rather, our results confirm that where fires ignite in relation to vegetation boundaries, topographic divides and the prevalent westerly airflow are key determinants of fire spread and extent, thereby, reducing the efficacy of the area burnt metric for our present analysis.

[12] Our results indicate that an increase (decrease) in fire activity during a fire-season (DJFMAM) is preceded by an anomalously dry (wet) year associated with a positive (negative) SAM phase. The one-year lag we have identified between SAM years and fire seasons reflects the high moisture content of fuels in this perennially wet landscape and the time required to precondition fuels to burn. The same lag between SAM and fire occurrence was not identified in the drier temperate forests in Patagonia studied by Holz and Veblen (2011), who based their analysis on fires inferred from fire-scarred trees in forests located close to the Patagonian forest-steppe ecotone. The forest-steppe ecotone environment in

Patagonia is considerably drier than southwest Tasmania [*Garreaud et al., 2009; Sturman and Tapper, 2006*] and, while hosting a high biomass load that does not limit fire [*Holz and Veblen, 2011*], less time would be required to condition the fuel in that landscape to burn when compared with southwest Tasmania. Thus, our analysis identifies SAM as the main driver of inter-annual fire activity across a broad swath of the Southern Hemisphere. Our results are consistent with the pervasive influence of the North Atlantic Oscillation (NAO), the northern counterpart of SAM, over fire regimes in forest ecosystems in North America, where NAO driven shifts in the Northern Hemisphere westerlies modulate temporal fire activity via their influence on hydro-climate [*Le Goff et al.,* 2007]. Indeed, evidence is mounting that a number of climate modes play a pivotal role in modulating long term fire activity in high biomass ecosystems globally [*Le Goff et al.,* 2007; *Holz and Veblen*, 2011; *Ramon-Cuesta et al.,* 2014; *Fletcher et al.,* 2015] and these relationships must be considered when attempting to predict future climate-fire trends [*Mortiz et al*., 2012].

[13] We identify tight coupling between landscape-wide fire activity in southwest Tasmania and a recent SAM reconstruction for the last millennium (Figure 4). This coupling is entirely consistent with our findings of significant correlation between SAM and fire activity in southwest Tasmania, revealing a persistence of this relationship over longer timescales. Initially high charcoal values are consistent with relatively dry conditions through the latter part of the Medieval Climate Anomaly (ca. 1050-600 cal yr BP). A salient feature of our analysis is the persistent increase in fire activity since 1500 CE, throughout the Little Ice Age (ca 600-100 cal yr BP). Comparison with the two leading proxy-based proxy-based SAM reconstructions [*Abram et al., 2014; Villalba et al., 2012*] reveals a very tight synchronicity

between hemispheric-scale reconstructions of SAM and southwest Tasmanian fire activity through the last 500 years. This period represents a phase in which SAM becomes progressively more positive, exceeding the range of SAM variability experienced over the last millennium [*Abram et al., 2014; Villalba et al., 2012*] and it is clear that this trend drove an increase in landscape burning in southwest Tasmania. The observed dramatic increase in fire in this region after 1800 CE is consistent with the timing of European colonisation and a series of landscape-scale wildfires in the mid to late 1800's [*Marsden-Smedley,* 1998]. Critically, the relationship between SAM and southwest Tasmanian fire activity persists through the 21st century, when anthropogenic activity induced a further positive shift in SAM [*Perlwitz et al.,* 2008], despite a move toward greater fire regulation in this landscape. Our results reveal a high sensitivity of the Tasmanian environment to SAM driven shifts in the SWW and heralds a significant threat for fire-sensitive ecosystems in this region.

[14] Fire activity is predicted to increase in temperate forest biomes under projections of future climate scenarios [*Moritz et al.,* 2012]. Our revelation of a clear link between inter-annual and centennial-scale SAM dynamics and fire activity in southwest Tasmania (and across the Southern Hemisphere) introduces an additional variable that must be considered when projecting and planning for the future of these important ecosystems. While, future trajectory and mean-state of SAM is uncertain as ozone levels recover [*Polvani et al.,* 2011; *Perlwitz,* 2011], it is imperative that we attempt to grasp Earth System teleconnections, such as climate-fire interactions. The implication that SAM drives hemisphere-wide fire activity adds to the vast array of natural systems that are influenced by this important component of the global climate system, such as stream discharge [*Lara et al.,* 2008], rodent population

fluctuations [*Murúa et al.*, 2003], insect outbreaks [*Paritsis and Veblen*, 2011], and coastal and marine ecosystem dynamics [*Forcada and Trathan*, 2009; *Schloss et al.*, 2012; *Alvain et al.*, 2013; *Weimerskirch et al.*, 2012]. Thus, the pervasive influence of SAM over the Earth System means that many SAM influenced or dependent systems may face deleterious effects resulting from the current anthropogenically-driven SAM trend, underscoring the need for studies such as ours which attempt to elucidate climate-biosphere interactions.

CONCLUSION

[15] This research constitutes the first attempt in disentangling the role of SAM in driving fire activity in Tasmania. We reveal that SAM is significantly linked with inter-annual fire occurrence (number of fires) in southwest Tasmania. Palaeofire analysis reveals a tight coupling between southwest Tasmanian fire activity and two proxy-based SAM reconstructions, revealing that SAM drives fire activity at multiple scales of time in this landscape. We observe a multi-century increase in fire activity in southwest Tasmania in tandem with a positive trend in SAM over the last 500 years and, importantly, we note a 21st century spike in fire activity in response to the anthropogenic influence on SAM brought by ozone depletion.

[16] Acknowledgements

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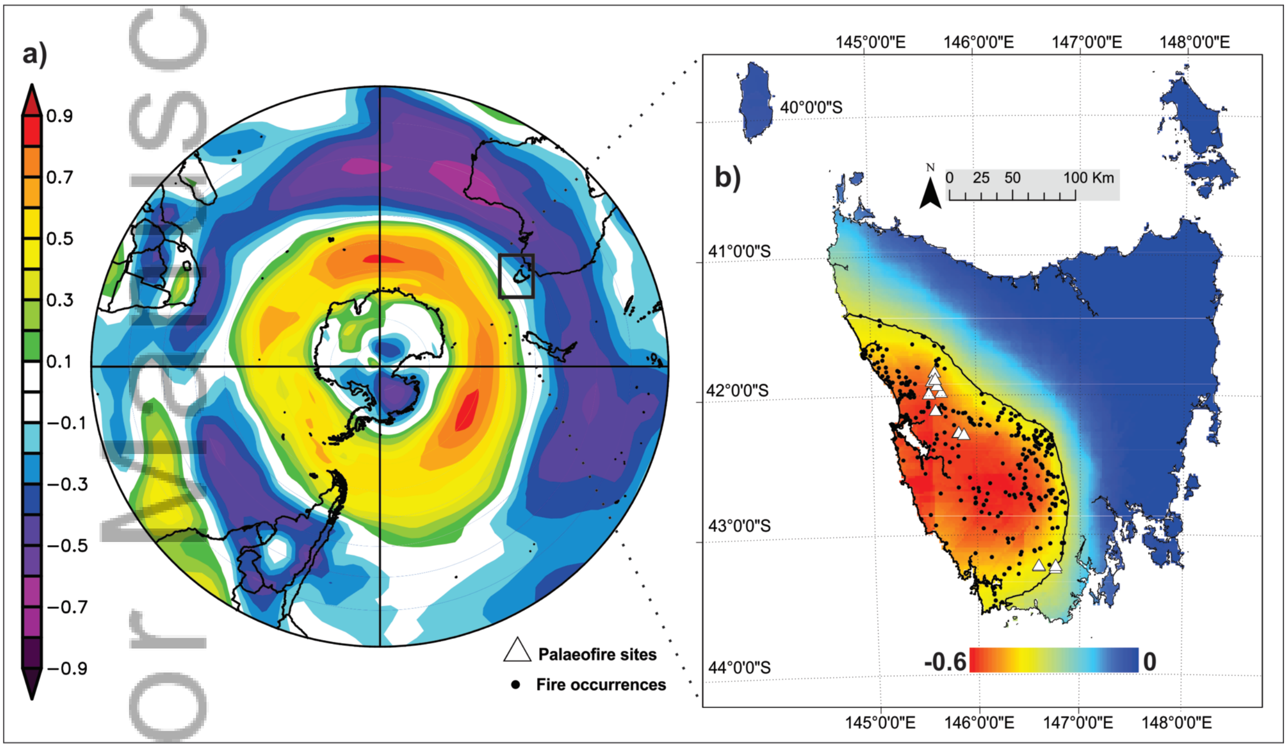
CAPTIONS

Figure 1a) Correlation map between zonal wind speed at 850 mb and the SAM index (all data sourced by NOAA) **b)** Map of the correlation between annual rainfall anomalies and annual SAM index across Tasmania. Solid line indicates the boundary of the SAM zone (*r*>0.3). Dots represent all the fires occurred between 1992 and 2014 within this area. White triangles indicates the sites used for the palaeofire analysis.

Figure 2 a) Annual SAM index (1992-2014) [Marshall, 2003] **b)** Number of fires and **c)** Area burnt in the SAM zone of influence in Tasmania (1992-2014). Black solid lines represent the respective weighted average of the annual SAM index and the number of fires.

Figure 3 Departures from mean values for annual SAM index obtained using SEA during **a)** fire years based on number of fires; **b)** non-fire years based on number of fires; **c)** fire years based on area burnt and **d)** non-fire years based on area burnt.

Figure 4 a) Paleofire charcoal composite of the SAM zone (50 year interval); **b)** SAM index reconstruction by Villalba *et al.* (2012); c) SAM index reconstruction by Abram *et al.*, 2014; grey solid line is the annual index, black solid line represents the 70-year LOESS smoothing of the yearly reconstructed SAM indices.



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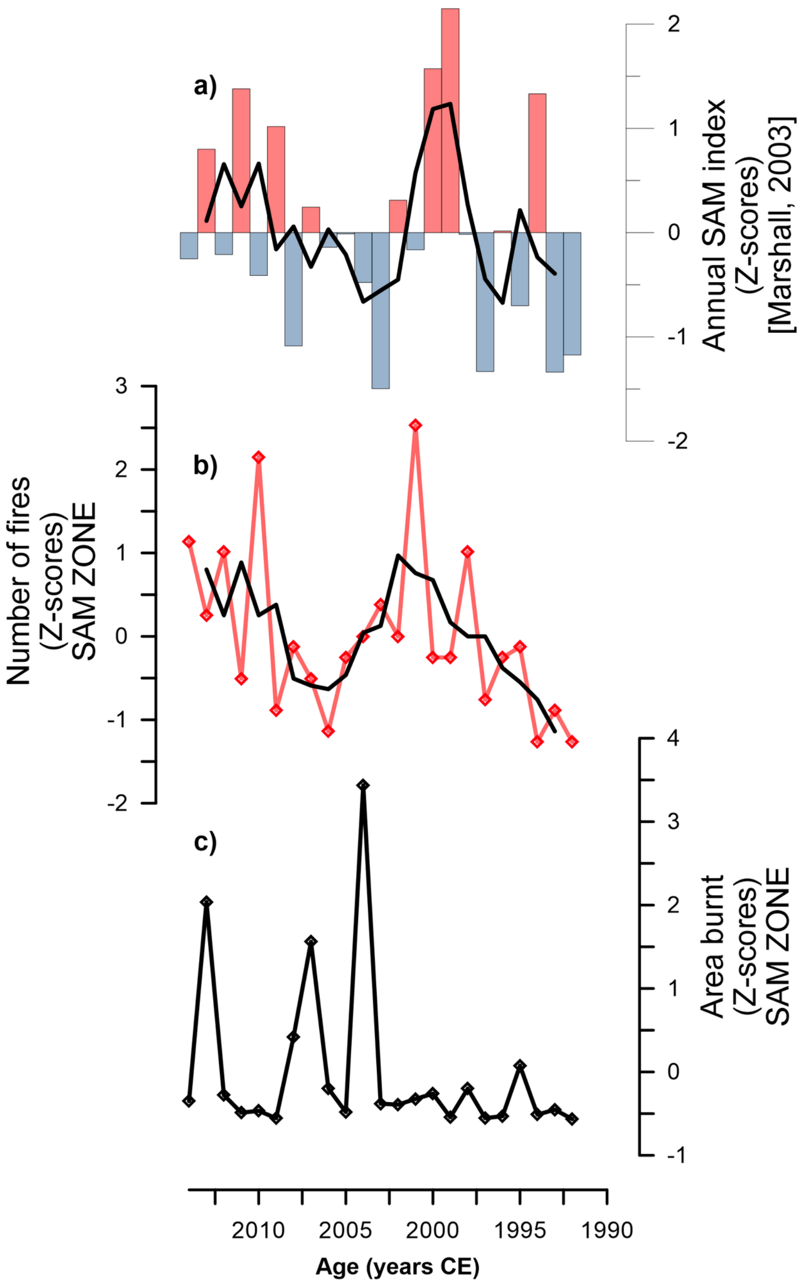

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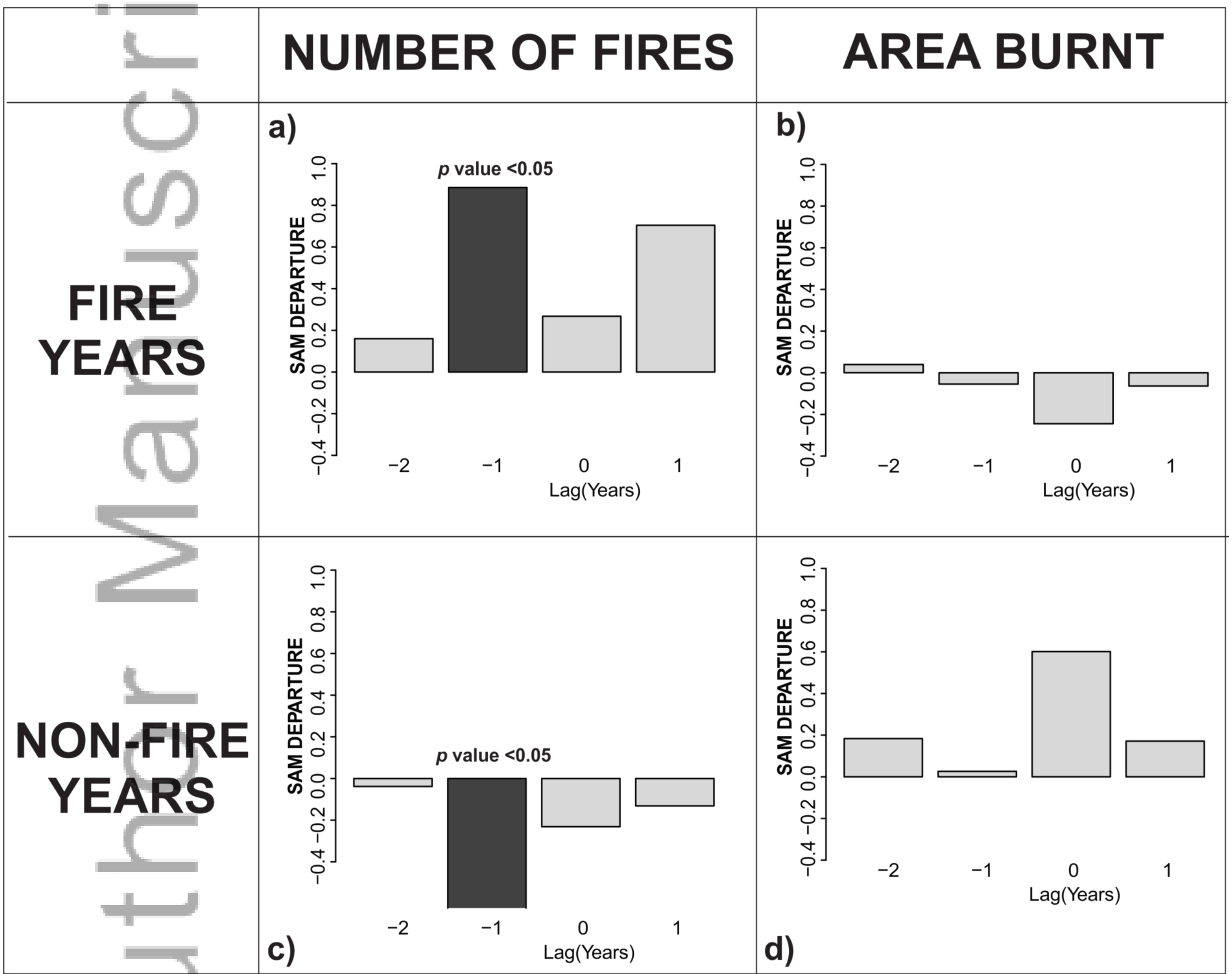

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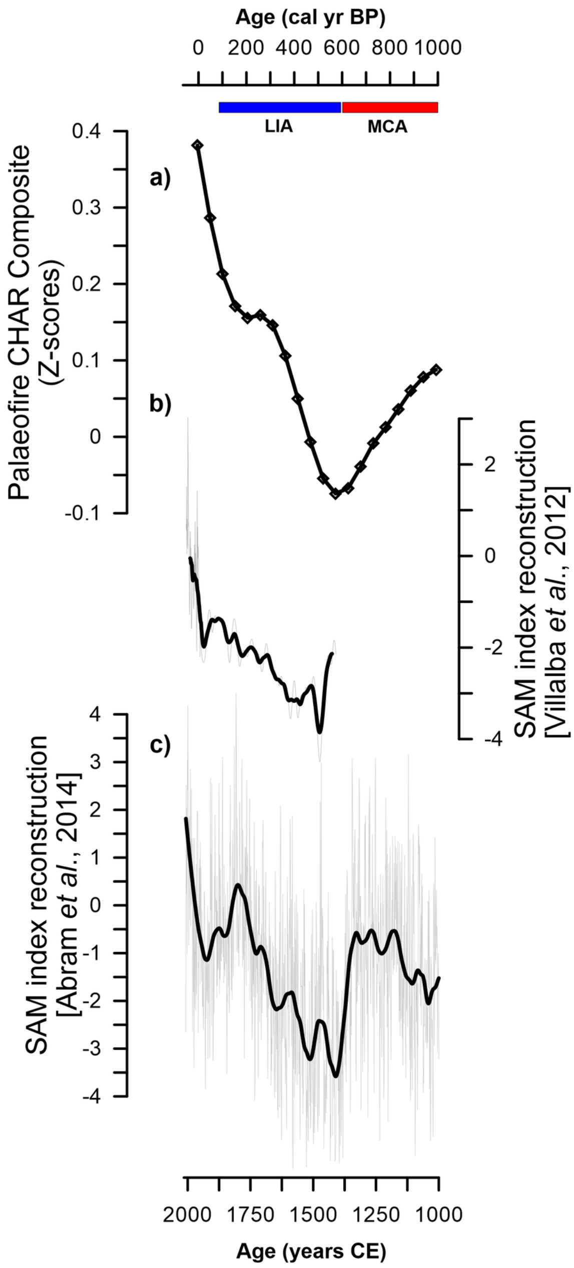

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