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Ecological and climatic controls of modern wildfire activity patterns across southwestern South America

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Abstract. Understanding how patterns of wildfire activity across biomes are shaped by heterogeneity in biomass resources to burn and atmospheric conditions conducive to burning is a high research priority in the context of global environmental change. Along a latitudinal gradient (25 to 56° S) from semi-arid scrublands through Mediterranean-type vegetation to wet forests in southwestern South America (SSA) we analyzed influences of mean climate and interannual climate variability on fire activity using documentary fire records from 1984 to 2008. We identified large regions with common temporal variability in annual area burned, related this variability to local interannual climate variability and in turn to modes of the major tropical and extratropical climate drivers of the southern hemisphere—El Niño-Southern Oscillation (ENSO) and the Antarctic Oscillation (AAO). Differences in fire activity response to interannual climate variability were related to the relative influences of available biomass to burn, and to weather effects on amounts of fine fuels and fuel moisture conditions. The pattern of average fire activity along this latitudinal moisture/productivity gradient corresponds well with the varying constraints model. This model predicts low fire activity towards the arid extreme due to reduced burnable biomass and again towards the humid extreme due to infrequent weather suitable for drying fuels, and predicts a broad zone of high fire activity at intermediate locations where resources to burn are abundant in all years and fuel moisture dries under reliably dry summer conditions. The dominant influence on interannual climate variability is AAO, which explained most of the variability in fire activity both by reducing seasonal precipitation in mesic and wet forests where fire is dependent on infrequent drought and by enhancing fine fuel production in Mediterranean-type vegetation where fuel amount and continuity constrain fire activity. In the context of the drying and warming trends in SSA related to the continued positive anomaly in AAO, our results underscore the importance of the varying constraints on fire activity and modulation of fire-climate relationships by different vegetation types, which is a much needed step toward developing fire projections under future climate.

Key words: annual area burned; Antarctic Oscillation; El Niño-Southern Oscillation; fire-climate relationships; fire ecology; Southern Annular Mode; wildfire.

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Introduction

Understanding how climatic and biological systems interact to create spatial and temporal patterns of wildfire activity over broad regions is an urgent need in the context of global environmental change (Bowman et al. 2009, Krawchuk et al. 2009, Moritz et al. 2012). Regional climate variability at interannual to inter-decadal time scales is often teleconnected to large-scale climate drivers such as El Niño Southern Oscillation (ENSO) that may synchronize fire activity over broad areas (Le Page et al. 2008, Wooster et al. 2012). Such relationships allow at least short-term forecasts (months to one or two years) of fire risk (Le Page et al. 2008, Prestemon et al. 2008). However, effects of interannual climatic variability on fire activity differ among biomes, because of differences in the constraints on wildfire activity related primarily to biomass resources to burn, atmospheric conditions suitable for combustion and propagation of fire, and sources of ignition (Krawchuk and Moritz 2011). For example, drought enhances wildfire potential in moist forest biomes where mean net primary productivity is relatively high and biomass resources are always available for burning; in contrast, in xeric areas where low productivity limits the availability of burnable fuels antecedent wet growing seasons may be the key constraint on area burned (Pausas and Bradstock 2007, Archibald et al. 2009, Littell et al. 2009, Krawchuk and Moritz 2011). Even within the same biome, fire activity along aridity/productivity gradients can be strongly affected by fuel characteristics, rate of fuel supply and fuel arrangement of the dominant vegetation types (Bradstock 2010). Contrasts in fuel types can modulate fire-climate relationships at a regional-scale in the same biome (Pausas and Paula 2012) and even at local scales (Gartner et al. 2012). Potential constraints on fire activity due to vegetation differences, both within climatically homogeneous regions and across different biomes, underscore the importance of considering ecological context in assessing effects of climate variability on past and future wildfire activity.

Increases in area burned since ca. 1980 have been reported for forested ecosystems in many parts of the world (Meyn et al. 2007, Flannigan et al. 2009). While changes in land-use practices in some regions have contributed to recent increases in wildfire activity (Meyn et al. 2007), global warming is believed to have an overriding role (Trenberth et al. 2007). Increased wildfire activity induced by rapid warming may change forested ecosystems from carbon sinks to carbon sources (Kurz et al. 2008). In addition, wildfire synchrony has been reported in widely separated areas at sub-continental to continental scales via atmospheric teleconnections of major climatic oscillations, such as ENSO (Kitzberger et al. 2001, Kitzberger et al. 2007, Le Page et al. 2008, Chen et al. 2011). Despite the uncertainty associated with specific wildfire trends (i.e., increase or decrease; Scholze et al. 2006, Trenberth et al. 2007), climate drivers and their teleconnections to regional and local climates are proving useful in explaining broad-scale synchrony and trends in wildfire activity (Le Page et al. 2008, Macias Fauria et al. 2011). However, research is needed on how vegetation types mediate relationships between wildfire activity and interannual climate variability at local and regional scales, and linkages to variation in major tropical and extra-tropical climate drivers. To date, most broad-scale fire-climate research has either focused on coarse-scale fire-climate teleconnection patterns without explicitly examining regional biophysical differences (Le Page et al. 2008) or has examined ecological constraints on how wildfire activity responds to climate variability without explicitly considering teleconnections to major climate drivers (Pausas and Bradstock 2007, Archibald et al. 2009, Bradstock 2010). Only a few studies (mostly in North America) have examined how differences in ecological provinces affect relationships of fire to large-scale climate drivers (e.g., Gedalof et al. 2005, Littell et al. 2009). To our knowledge, no other empirical studies have examined how local to regional-scale climate anomalies teleconnected to variability in major climate drivers differentially affect wildfire activity across ecosystem types ranging from arid lands to Mediterranean-type ecosystems, and to mid- to high-latitude temperate rainforests.

In the southern hemisphere, the west coast of southern South America (SSA) provides one of the Earth's latitudinally most extensive continuous land mass of contrasting climates of increasing moisture availability through arid-subtropical, Mediterranean-type, and temperate/

sub-Antarctic latitudes (ca. 17 to 56° S). This latitudinal gradient of moisture availability and biomes provides an opportunity for examining the effects of interannual climate variability and ecological constraints on wildfire activity. In this study, we focus on effects of weather over periods of ca. 3 to 18 months on fire activity across a range of biome types reflecting influences of longer-term average climate on mean net primary productivity and biomass resources to burn (sensu Krawchuk and Moritz 2011).

In SSA major tropical and extra-tropical drivers of climate variability induce anomalous patterns of temperature and precipitation through their influences on the latitudinal position and intensity of the southeast Pacific subtropical high-pressure system and the southern westerly winds (SWW; Aceituno 1988, Garreaud and Aceituno 2007, Garreaud et al. 2009). In turn, anomalies of these synoptic-scale climate patterns have been linked to annual variability in wildfire activity in particular subregions based on late 20th century documentary fire records (Kitzberger et al. 1997, Veblen et al. 1999, Kitzberger and Veblen 2003, Whitlock et al. 2007). In mid-latitude mesic forests (at ca. 37 to 43° S) increases in fire activity coincide with periods of drought strongly associated with annual variability in the intensity and latitudinal position of the SE Pacific Anticyclone which is also linked to ENSO and SWW anomalies. In SSA tree-ring reconstructed fire history studies have linked forest fire activity over several centuries to drought events teleconnected to ENSO, the Pacific Decadal Oscillation (PDO), and the Antarctic Oscillation (AAO or the Southern Annular Mode, SAM) (Kitzberger and Veblen 1997, Veblen et al. 1999, González and Veblen 2006, Holz and Veblen 2012, Mundo et al., *in press*). For example, tree-ring reconstructed fire histories from northern (40–42° S) and central (43–48° S) Patagonia, show that drought events strongly associated with years of positive AAO result in widespread wildfires (Holz and Veblen 2011).

AAO is a see-saw pattern of synchronous zonal pressure anomalies between mid- and high-latitudes and its positive phase strengthens and shifts poleward the SWW (Thompson and Solomon 2002, Garreaud et al. 2009). A positive trend in the AAO since 1950 has been linked to warming effects of greenhouse gasses and to depletion of stratospheric ozone (Thompson and Solomon 2002), and it is expected that AAO will remain in its positive phase over the next century (Miller et al. 2006, Polvani et al. 2011, Thompson et al. 2011). In addition, multi-century tree-ring fire histories in southwestern Patagonia indicate that the fire-promoting influence of AAO is enhanced when sea surface temperatures (SST) in the tropical and temperate Pacific are anomalously warm (Holz and Veblen 2012). Analogous to the fire-promoting upward trend in AAO, a broad-scale warming trend during the second half of the 20th century is well documented for the southern hemisphere (Dettinger et al. 2001, Garreaud et al. 2009). Specifically for northern and southern Patagonia (37–46° S and 46–55° S, respectively), tree-ring reconstructions indicate that mean annual temperatures for 1900–1990 are 0.53° and 0.86°C above the 1640–1899 means, respectively (Villalba et al. 2003).

Existing analyses of modern (i.e., late 20th century) documentary fire records in SSA have examined climate-fire relationships for only limited geographical areas and a small portion of the biomes of SSA (Kitzberger et al. 1997, Veblen et al. 1999, Kitzberger 2002, Whitlock et al. 2007, Moreno et al. 2010). No previous studies have systematically examined the consistency of fire-climate relationships across a range of vegetation types despite the expectation that weather influences on fire activity are likely to differ greatly along the latitudinal gradient from arid scrublands to moist forests. According to the varying constraints hypothesis of Krawchuk and Moritz (2011), drier weather conditions immediately prior to or during the fire season are expected to increase fire activity in biomass-rich ecosystems such as mesic forests that without anomalously dry periods have fuels that are too wet to easily burn. At the opposite end of an aridity gradient, the dominant limiting factor for fire is amount or connectivity of fine fuels, such as in some grasslands and sparse shrublands. Under this conceptual framework, areas that on average are dry have unfavorable conditions for burning due to lack of fuels, whereas the best conditions for burning occur under intermediate average moisture conditions that allow for coexistence of high fuel accumulation and frequent occurrence of seasonally dry conditions

(Krawchuk and Moritz 2011). For example, along aridity/productivity gradients fire activity generally rises from very low levels at the arid extreme to high levels at intermediate moisture positions and declines again to low levels at the wet extreme (Pausas and Bradstock 2007, Bradstock 2010). Thus, for SSA along the aridity/productivity gradient from arid lands in the north to wet forests in the south we generally expect maximal fire activity near the center of the gradient. However, for specific points along the gradient we lack understanding of where fuel structure (biomass available to burn) is more controlling of fire activity as opposed to frequency of seasonal to annual climatic conditions conducive to fuel desiccation.

The overall goal of our study is to assess the influence of interannual climate variability (i.e., weather over 3 to 18 month periods) on fire activity at local and regional scales along an extensive latitudinal moisture gradient, and to examine the influence of regional-scale teleconnections to local climate and fire based on documentary fire records for the 1984 to 2008 period. Specifically, the objectives of our study are to: (1) determine the latitudinal pattern in average relative areas burned (separately for woody- versus herbaceous-dominated vegetation) along the gradient from semi-arid Mediterranean-type ecosystems through cool temperate/sub-Antarctic rainforests in SSA, (2) identify regions with common temporal variability in annual area burned (AAB) and examine how this variability is associated with anomalies in both local climate and in major tropical and extra-tropical climate drivers indexed as ENSO and AAO, and (3) assess the role of dominant fuel types in distinguishing these regions of common temporal variability in AAB and the respective relationships between local climate anomalies and major climate drivers. We used government documentary fire records to develop a time series of AAB in woody and herbaceous vegetation separately from 25 to 56° S (ca. 3,350 km) to identify geographical regions of known physiognomic vegetation types that showed similar temporal patterns of interannual variability in wildfire activity. AAB for these geographical regions was correlated with meso-scale patterns in seasonal precipitation and temperature, and then with variability in regional-scale climate drivers and anomalies in regional ocean/atmospheric circulation patterns. We then propose underlying ecological mechanisms that explain the varying fire-climate relationships along this latitudinal/moisture gradient.

Methods

Study area

The north-to-south gradient of biophysical features of the study area in SSA (Fig. 1) is an approximate analogue of the south-to-north moisture gradient from northwestern Mexico to southeast Alaska in North America. The climate of our study area has three key gradients relevant to patterns of vegetation and wildfire activity: (1) a poleward decrease of annual and especially summer temperature, (2) a poleward trend towards overall increase in winter and annual precipitation and a seasonally equitable distribution of precipitation, and (3) an orographic and elevation-related increase in precipitation and decrease in temperature from the coast to the Andean summits followed by a rainshadow effect east of the Andes. South of ca. 45° S, rainfall is almost evenly distributed throughout the year, whereas north of ca. 37° S summers are typically dry (Kitzberger et al. 2001, Garreaud et al. 2009). Annual precipitation variability is determined by changes in the strength and latitudinal position of the southeast Pacific subtropical anticyclone and westerly storm tracks that fluctuate between 45-55° S in the summer to 35–45° S in the winter (Nakamura and Shimpo 2004, Garreaud et al. 2009). The longitudinal central valley of Chile of mostly agricultural and urban land use is flanked by the Coastal Range to the west and the Andes to the east from ca. 28 to 40° S. Bioclimatically, the study area encompasses from north-to-south three distinct zones: the Mediterranean zone from ca. 25 to 36° S, the Temperate zone from ca. 37–53° S, and the Sub-Antarctic zone from ca. 54 to 56° S, plus two transitional zones (i.e., Mediterranean/Temperate and Temperate/Sub-Antarctic zones) (Amigo and Ramírez 1998). Biomes (following Veblen et al. 1983, Gajardo 1994) are mostly distinguished by their north-to-south position so that there is an approximate match between dominant biome type and the government administrative districts that are also arranged

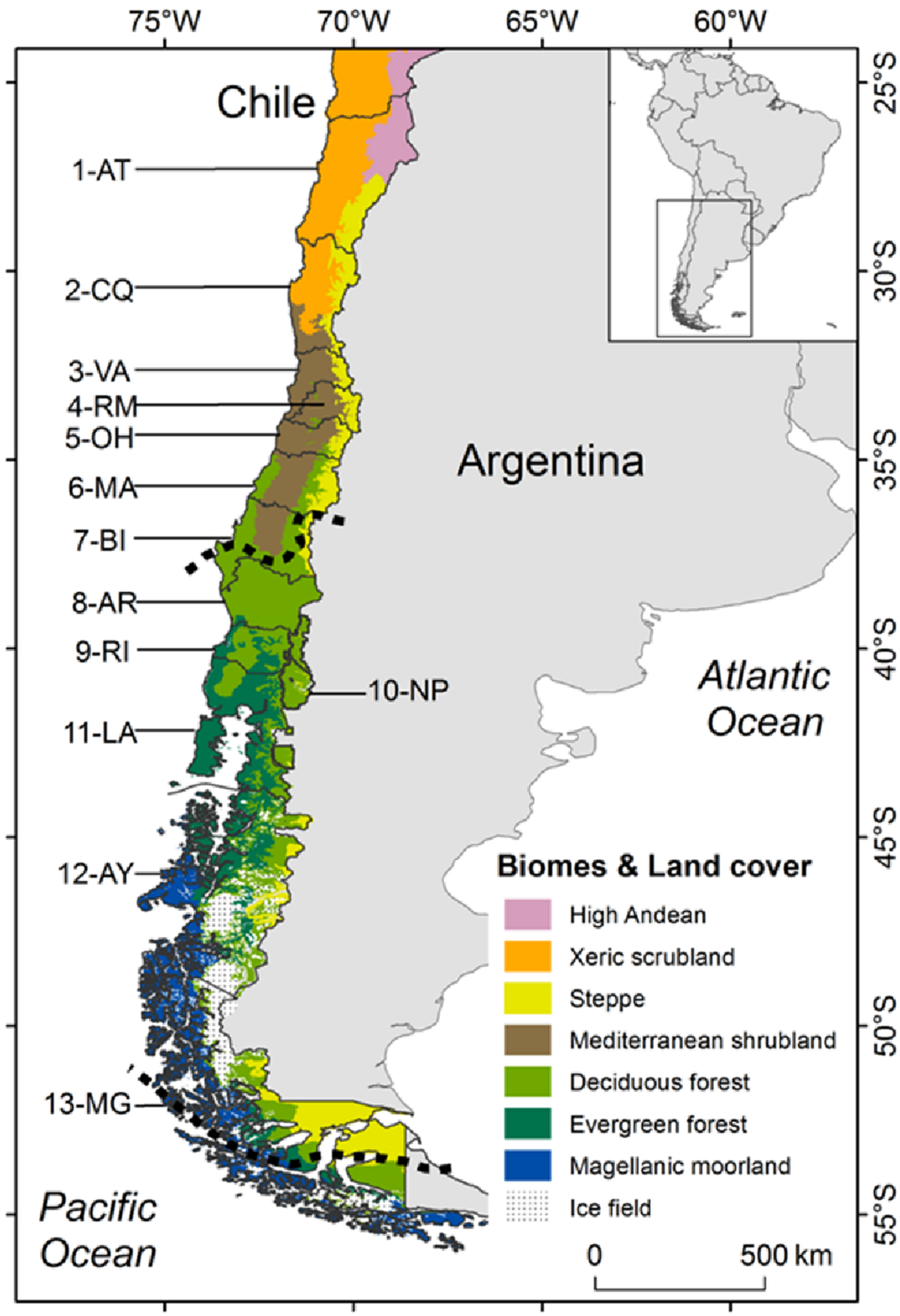

Fig. 1. Study area showing biomes, land cover and bioclimatic zones. Biomes and land cover types are modified after Gajardo (1994) and Veblen et al. (1983). The bioclimatic zones for the study area are adapted from Amigo and Ramírez (1998), and from-north-to-south are: Mediterranean, Temperate, and Sub-Antarctic, plus two transitions zones (i.e., Mediterranean/Temperate and Temperate/Sub-Antarctic zones; thick dotted black lines). The 12 political districts in Chile and the aggregated Argentinean National Park dataset are presented in detail in Table 1, including their dominant biomes and bioclimatic zones.

Table 1. Characteristics of the administrative districts analyzed in this study.†

Bioclimatic zone‡	Dominant biome§	Administrative district	Code	Latitude (°S)	Total area (ha × 10^6)
Mediterranean	Xeric Scrubland	Atacama	1-AT	26–29	7.6
		Coquimbo	2-CQ	29–32	4
	Mediterranean Shrubland	Valparaíso	3-VA	32–33	1.6
		Metropolitana	4-RM	33–34	1.5
		O'Higgins	5-OH	34–35	1.6
		Maule	6-MA	35–36	3
Mediterranean/Temperate	Mediterranean Shrubland/ Deciduous Forest	Bio-Bio	7-BI	36–38	3.7
Temperate	Deciduous Forest	Araucanía	8-AR	37–40	3.1
		Los Ríos	9-RI	40–41	1.8
		4 National Parks (Argentinean Lake District)	10-NP	39–43	1.4
	Broadleaved-evergreen Forest	Los Lagos	11-LA	41–44	4.8
		Aysén	12-AY	44–49	10.7
	Magellanic Moorland	Magallanes	13-MG	49–53	9.4
Temperate/Sub-Antarctic	Magellanic Moorland	Magallanes	13-MG	53–54	1
Sub-Antarctic¶	Magellanic Moorland	Magallanes	13-MG	54–56	2.8

† See Appendix B.
‡ Bioclimatic zones from Amigo and Ramírez (1998).
§ Classification of the dominant biomes follows Veblen et al. (1983) and Gajardo (1994).
¶ We used the name "Sub-Antarctic" instead of "Boreal" that was originally suggested by Amigo and Ramírez (1998).

from north to south (Fig. 1, Table 1). Also from north to south, the length of the fire season tends to shorten (i.e., Nov–Apr in the Mediterranean zone and Jan–Mar in the Temperate/Sub-Antarctic zones; CONAF, *unpublished data*).

The northern zone encompasses arid and semiarid regions in northern and central Chile that are considered together in the current analysis as the "Mediterranean" zone (Fig. 1). The arid region is dominated by xeric scrubland, and high Andean steppe (i.e., grass and dwarf shrubs) biomes in the 1-AT and 2-CQ administrative districts (ca. 26–31° S/70° W; Fig. 1; Table 1). Semi-arid central Chile is characterized mainly by Mediterranean type sclerophyll shrubland and high Andean steppe from the 3-VA through the 6-MA administrative districts (ca. 32–36° S/ 71–72° W). In this region, the remnants of sclerophyll shrublands occur mainly in the Central Valley, and a mosaic of mostly deciduous *Nothofagus* forest and shrublands occur in the coastal and Andean foothills. Towards the south, the Mediterranean-Temperate transition zone includes sclerophyll shrublands and deciduous *Nothofagus* forests in the 7-BI administrative district (ca. 36–38° S/73° W). In this region, large areas of exotic tree (pines, eucalypts, and poplars) plantations have been established mostly since the 1970s in the Coastal Range (Appendix A: Table A1). However, exotic tree plantations were not included in the current analysis due to their apparently greater flammability compared to native woody vegetation.

The extensive Temperate bioclimatic zone (ca. 37–53° S) is subdivided into three sub-regions: (1) a warm-wet Temperate region on the western flank of the Andes from ca. 37 to 41°S of mainly deciduous forests in administrative districts 8-AR and 9-RI; (2) a cool-wet Temperate region from ca. 41 to 53° S of evergreen (both conifers and angiosperms) forests in the west and towards the east deciduous forests and Patagonian steppe, mostly in administrative districts 11-LA and 12-AY; and (3) a dry temperate region from ca. 39 to 43° S on the eastern side of the Andes in Argentina of evergreen forests in the west and deciduous *Nothofagus* forests and steppe to the east in administrative district 10-NP (Fig. 1). In administrative districts 12-AY and 13-MG, the western archipelago is characterized by Magellanic moorland, where extensive areas of poor drainage are interspersed with patches of rocky ground with generally thin soil, and the vegetation is a mosaic of blanket peat and low-growing shrubs with small stands of evergreen trees in more sheltered areas. To the east there are successive belts of evergreen *Nothofagus* forest, deciduous forest, and steppe. In the steppe, anthropogenic pastures for ranching activities are common (Fig. 1). In the Sub-Antarctic zone (represented by administrative district 13-MG) extensive areas of Magellanic moorland occur in the southwest but again there is a forest to steppe gradient towards the east (Fig. 1).

Descriptive statistics of fire activity along the latitudinal moisture gradient

We used annual area burned (AAB) in wildfires reported for administrative districts based on incident reports and maps by the Chilean and Argentinean forest and park services (CONAF and APN, respectively). Since the fire season in SSA spans over two calendar years (Nov–Mar), we assigned annual AAB to the earlier calendar year (i.e., following the dendrochronological convention for the Southern Hemisphere; Schulman 1956). Fire incident reports and maps have been checked for accuracy in the field extensively in Argentina (Mermoz et al. 2005) and for selected areas south of 42° S in Chile (current study). The administrative districts include 12 districts in Chile and one district in northern Patagonia, Argentina, numbered for simplicity from 1 to 13 from north to south (Table 1; Fig. 1; Appendix A: Table A1). In this analysis we only used AAB in native vegetation (Appendix A: Table A1). Reliable and methodologically consistent time series of AAB for forest and shrublands combined (hereafter woody vegetation) and for grasslands (hereafter herbaceous vegetation) extend from 1984 to 2008 (Table 1; Appendix B). We combined AAB from forest and shrublands because: (1) both are dominated by long-lived woody plants where following first principles it is likely that fuel amount is sufficient to carry fires, (2) for the most part tall dense shrublands are inter-mixed with forests in some of the Mediterranean areas and are successional to forests in the southern area, and (3) previous work (Kitzberger et al. 1997) reported that grasslands have a different fire-climate signal from dense tall shrublands and forests. Accordingly, all analyses were conducted for woody vegetation separately from herbaceous vegetation to examine potential differences within the same administrative district and along the moisture gradient. To describe fire activity along the latitudinal moisture gradient, we separately computed anomalies in relative area burned in woody and herbaceous ecosystems as the percentage (%) of available area that burned in each administrative district over the period 1984 to 2008 (Appendix A: Table A1).

Identification of regions of common temporal patterns of annual area burned

To identify common temporal patterns of AAB among the 13 districts we conducted PCAs of woody vegetation and of herbaceous vegetation datasets. Each dataset was (1) first log-transformed, (2) normalized (by computing departures from the mean in standard deviation units), and (3) grouped into regions of similar temporal variability using a singular value decomposition on the covariance matrix of the time series of AAB anomalies applying a varimax (orthogonal) rotation. We used the scree plot curve slope and the Jolliffe cut-off value (Jolliffe 1986) to guide the selection of a significant number of PCs to interpret each dataset. In addition, the PC loadings were mapped onto each of the administrative districts to reveal spatial signatures of each of the PCs for both vegetation types.

Climate data and indicators of climate modes

Precipitation and temperature data were obtained for grids of 0.5° latitude by 0.5° longitude from the Center for Climatic Research of University of Delaware (Legates and Willmott 1990*a*, *b*; hereafter "UDel data"); data were downloaded from the website of NOAA/OAR/ESRL PSD, Boulder, Colorado, USA (http://www.esrl.noaa.gov/psd/). The indices of large-scale climate drivers linked to variation in regional climate conditions considered in the current study are: the Multivariate ENSO Index (MEI) and the Antarctic Oscillation (AAO) index. The MEI is based on six observed variables over the tropical Pacific: sea surface temperature (SST), surface air temperature, sea-level pressure (SLP), zonal and meridional components of the surface wind, and total cloudiness fraction of the sky (Wolter and Timlin 1993, 1998, 2011). The AAO index is based on the seasonal AAO index of the Climate Prediction Center (NOAA; www.cpc.noaa.gov/, 1979–2012), which is defined as the first leading mode from the empirical orthogonal function analysis of monthly mean height anomalies at 700 hPa poleward of 20° S. In addition to these indices of ENSO and the AAO, we also used seasonal 700 hPa geopotential heights and seasonal SST (NCEP-NCAR Reanalysis; Kistler et al. 2001; http://www.esrl.noaa.gov/psd/data/gridded/reanalysis/; hereafter "NCEP data") for describing spatiotemporal relationships of climate and fire.

Analyses of fire-climate relationships

Spatial correlation analyses were used to identify the main climatic influences on the variability of spring-summer (Sep–Mar) patterns of wildfire activity in SSA. First, spatial correlations were conducted between the selected PCs and UDel's records to identify the most relevant local climatic parameters (i.e., precipitation and/or temperature by season) associated with high fire activity. We computed correlations during the year of the fire and during the year previous to the fire season. Seasonal values used are: fall (Mar–May), winter (Jun–Aug), spring (Sep–Nov), summer (Dec–Feb). Second, climatic parameters associated with high fire activity were correlated with the MEI and AAO indices to examine potential teleconnections between local climate conditions and large-scale climate drivers. Third, to examine potential teleconnections between these large-scale climate drivers and fire, we used spatial correlations between the selected PCs and global and regional ocean/atmospheric circulation patterns that define ENSO and AAO. From the NCEP data, we used seasonal sea surface temperatures (SSTs) and 700-hPa geopotential height to reflect variability in seasonal ENSO and AAO indices, respectively, and correlated them with selected PCs. For all analyses above, significance levels of the correlation values were determined using 23 degrees of freedom since the PC time series do not show any autocorrelation and consequently are assumed to be independent. With 23 degrees of freedom, Pearson's correlation coefficients of $>0.51/<-0.51$, $>0.40/<-0.40$, and $>0.34/<-0.34$ are significant at the 99%, 95%, and 90% confidence levels (CI%) for a two-tailed test, respectively. Where the correlation analyses yielded correlations among several predictor variables or multiple fire seasons, we emphasize the correlations that are non-redundant and that mechanistically are the most explanatory.

Results

Fire activity along the latitudinal moisture gradient

Woody vegetation.—Measures of central tendencies of fire activity for each fire-reporting district arranged from north to south along the latitudinal gradient exhibit lowest values at the dry and wet extremes (Fig. 2a). Biomass-limited ecosystems in north-central Chile (1-AT and 2-CQ; ca. 26–32° S), and ecosystems in which fuels infrequently are dry in southernmost Chile (12-AY and 13-MG; ca. 44–55° S) showed the lowest fire activity in relation to their respective available area to burn (Fig. 2a). In contrast, in central and south-central Chile (Mediterranean/Temperate transition zone; 3-VA through 11-LA, ca. 33–43° S), fire activity is relatively high in ecosystems that have both abundant burnable biomass and relatively frequent fuel-drying weather (Fig. 2a). The low variance in fire activity in the central portion of gradient (ca. 33–40° S) is consistent with the regularity of warm dry summers at these latitudes.

Herbaceous vegetation.—The latitudinal trend of fire activity in grasslands is generally similar to the pattern found for woody vegetation with the lowest fire activities again occurring in the extreme north and south (i.e., north of ca. 33° S and south of ca. 42° S; Fig. 2b). During the 1984–2008 period, fire activity in herbaceous vegetation was highest in central and south-central Chile (Mediterranean/Temperate transition zone; from 3-VA through 11-LA, ca. 33–43° S), with less fire activity at the two ends of the moisture gradient (1-AT and 2-CQ at ca. 26–32° S; 11-LA, 12-AY and 13-MG at ca. 41–55° S; Fig. 2b). Fire activity in herbaceous vegetation has the highest variance for the one district located entirely east of the Andes (10-NP).

Spatial patterns of annual area burned

Woody vegetation.—Nearly three fourths of the variance in the normalized AAB in forest and shrublands among the 13 administrative districts was explained by the first four components from a rotated PCA during 1984–2008 (24%, 23%, 13% and 11% for PC1, PC2, PC3 and PC4, respectively; Fig. 3a-c). According to the grouping of administrative districts7-BI, 8-AR and 9-RI towards the high end of PC1 (Mediterranean/

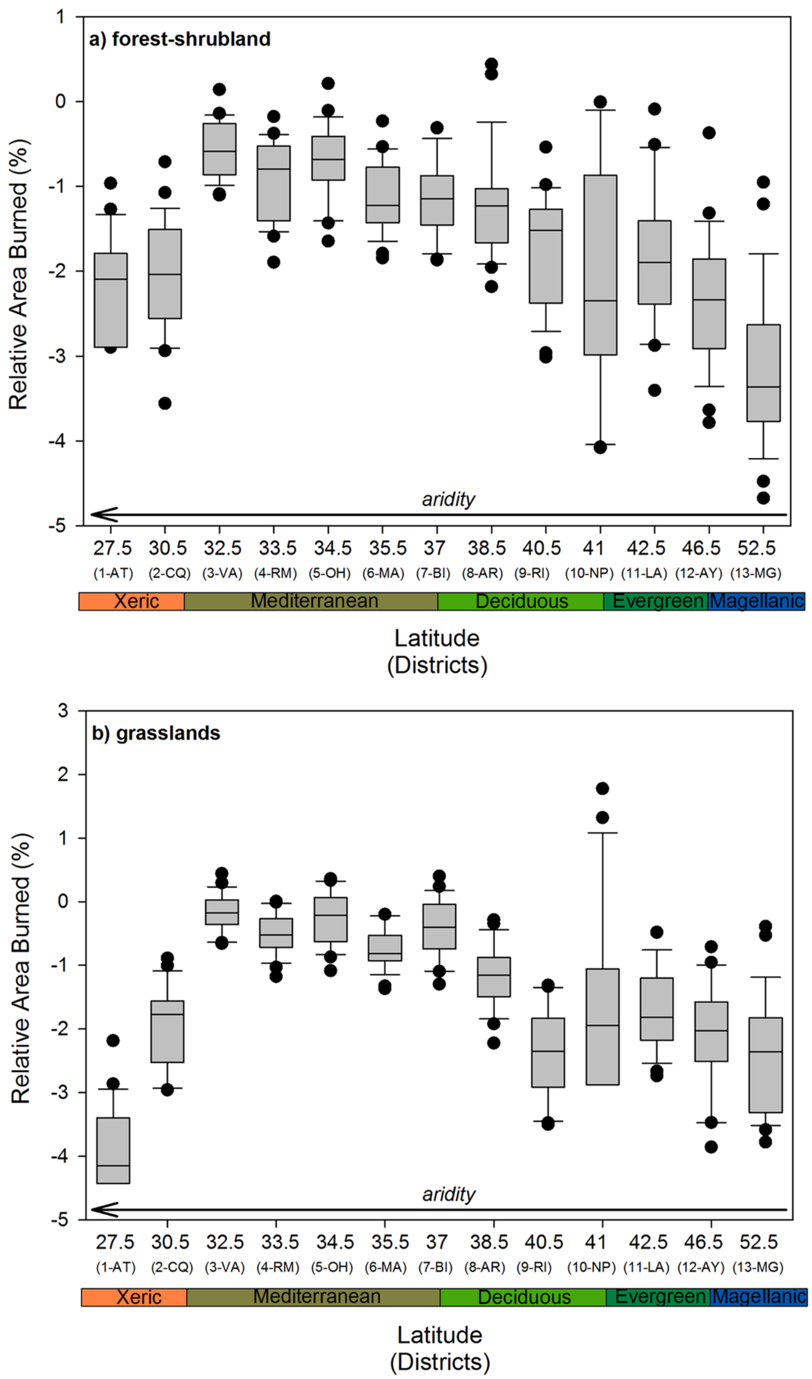

Fig. 2. Relative area burned (%; area burned in relation to available area per administrative district) in (a) woody vegetation (forest and shrublands) and (b) herbaceous vegetation (grasslands) arranged along the latitudinal moisture gradient in southern South America. Both records were normalized to a standard Z-score before plotting. The boundary of the box closest to zero indicates the 25th percentile, the line within the box marks the median, and the boundary of the box farthest from zero indicates the 75th percentile. Whiskers above and below the box indicate the 90th and 10th percentiles, and the small circles represent the outliers. Note the log-scale in y-axes.

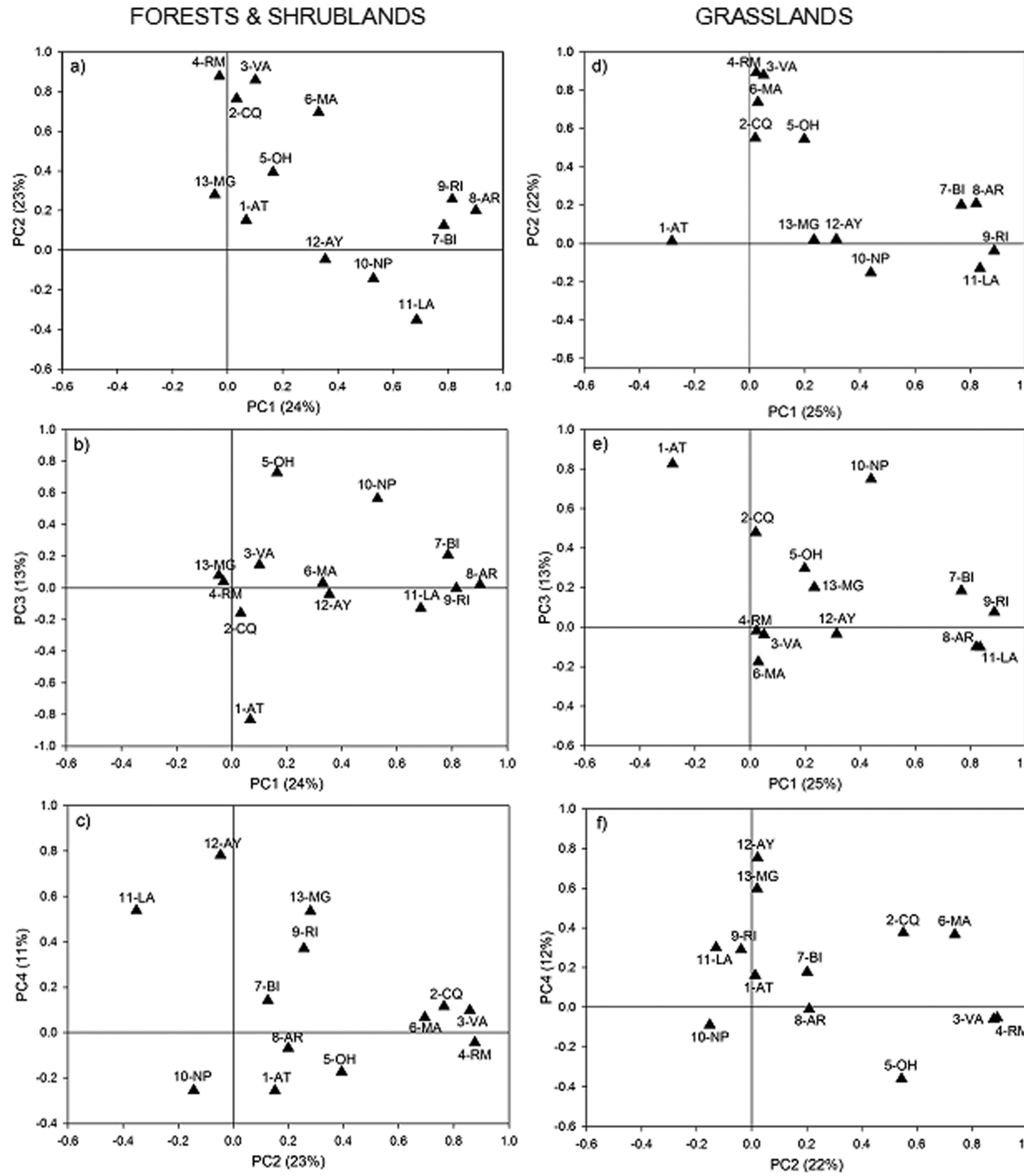

Fig. 3. Principal component analysis (PCA) of the normalized annual area burned (AAB) in southern South America (SSA). Loadings of the first four PCs of a Varimax rotated PCA of AAB in woody vegetation (a–c) and herbaceous vegetation (d–f) during the 1984–2008 period. AAB data is from 12 administrative districts in Chile and an aggregated set from four national parks in Argentinean North Patagonia (10-NP; Lanin, Nahuelhuapi, Puelo, and Alerces). For the woody vegetation dataset the explained variances are: 24%, 23%, 13%, and 11% for PC1, PC2, PC3 and PC4, respectively. For the grassland dataset the explained variances are: 25%, 22%, 13%, and 12% for PC1, PC2, PC3 and PC4, respectively. For description of the administrative districts see Table 1.

Temperate transition zone and warm-wet Temperate zone; ca. 36–41° S), this axis appears to reflect a tripole structure with a synchronous region in south-central Chilean and two opposite phase regions in the north (ca. 30–32° S) and far south (ca. 53° S) (Figs. 3a and 4a, Table 1). A second mode of variability represented by PC2 shows a bipolar structure with a main mode of variability in AAB in the Mediterranean zone and with the opposite phase region centered at ca. 42° S (Figs. 3a and 4b, Table 1). Between PC1 and PC2, roughly half of the variance of AAB of woody vegetation was explained. A third mode of variability in AAB expressed as PC3 identified a disjunct group (Mediterranean zone and dry Temperate zone) that encompasses the administrative districts of 5-OH, 7-BI (ca. 35–37° S) and the eastern 10-NP (ca. 41° S), with an opposite phase region in the northernmost district (1-AT; Figs. 3b and 4c, Table 1). The fourth mode of variability represented by PC4 shows a highly coherent region centered over the southern Chilean districts of the cool-wet Temperate zone (mostly 12-AY, but also 11-LA and 13-MG) while other northerly and east Andean districts are in the opposite phase (Figs. 3c and 4d, Table 1).

Herbaceous vegetation.—The general spatial pattern of AAB in grassland wildfires tends to follow the pattern found with the woody vegetation. Close to three fourths of the variance in grassland wildfire activity among the 13 administrative districts was explained by the first four components from a rotated PCA of the AAB during 1984–2008 (25%, 22%, 13% and 12% for PC1, PC2, PC3 and PC4, respectively; Fig. 3d-f). According to the grouping of administrative districts 7-BI, 8-AR, 9-RI, and 11-LA towards the high end of PC1 (warm-wet Temperate zone), this axis appears to reflect variability in AAB in grasslands in south-central Chile (ca. 36–43° S) (Figs. 3d and 4e; Table 1). PC2 mostly expressed variability in AAB further to the north in the Mediterranean zone in Central Chile, with an opposite phase region in south-central Chile and the 10-NP district in Argentina (Figs. 3d and 4f; Table 1). Roughly half of the variance of AAB of herbaceous vegetation was explained by PC1 and PC2 combined. A third mode of variability in AAB expressed as PC3 identified a disjunct group that includes the northernmost district (1-AT, ca. 28° S) and the 10-NP district (ca. 41° S) on the Argentinean eastern Andean slope (xeric zone and dry Temperate zone; Figs. 3f and 4g; Table 1). The fourth mode of variability PC4, shows a highly coherent region centered over the southern Chilean districts (cool-wet Temperate zone; 12-AY and 13-MG), while central Chilean districts are in the opposite phase (Figs. 3f and 4h, Table 1).

Wildfire activity associated with local climate, climate drivers and synoptic climatic patterns

Woody vegetation.—The main spatiotemporal pattern of normalized AAB expressed as PC1 scores (representing increased fire in woody vegetation in the Mediterranean/Temperate transition zone and warm-wet Temperate zone), was inversely correlated with precipitation during the spring of the fire year, with less precipitation influence during other seasons, and with no influence of temperature during any season over the 1984–2008 period (Fig. 5a, b). In turn, spring precipitation was inversely correlated with spring AAO and positively correlated with spring MEI during the same period, with the former relationship having the highest significance for most of the geographical extent of the PC1 region (Fig. 6i). Furthermore, PC1 was positively correlated with spring and summer AAO of the fire season, and negatively correlated with fall MEI (increased fires associated with La Niña phase) a year prior to the fire season (Table 2). When PC1 was high during the spring, upper-level pressure was weaker than normal at high-latitudes and greater than normal at mid-latitudes (zonally) across the southern hemisphere (Fig. 7a). These annular upper-level pressure anomalies are characteristic of the positive phase of AAO, and result from a southward shifted and strengthened SE subtropical Pacific anticyclone off the coast of Chile (Fig. 7a). The anticyclone blocks the SSW reducing mid-latitude zonal flow and rainfall in the region represented by positive values of PC1. Note however, that despite the relatively wide zone of reduced precipitation (ca. 27–50° S), the area of increased fire activity was restricted to ca. 35–45° S (Fig. 5a) in the Temperate forest zone and the transition to the Mediterranean-Temperate transition. East Tropical Pacific SSTs show no significant correlation pattern with PC1 scores (Fig. 7b).

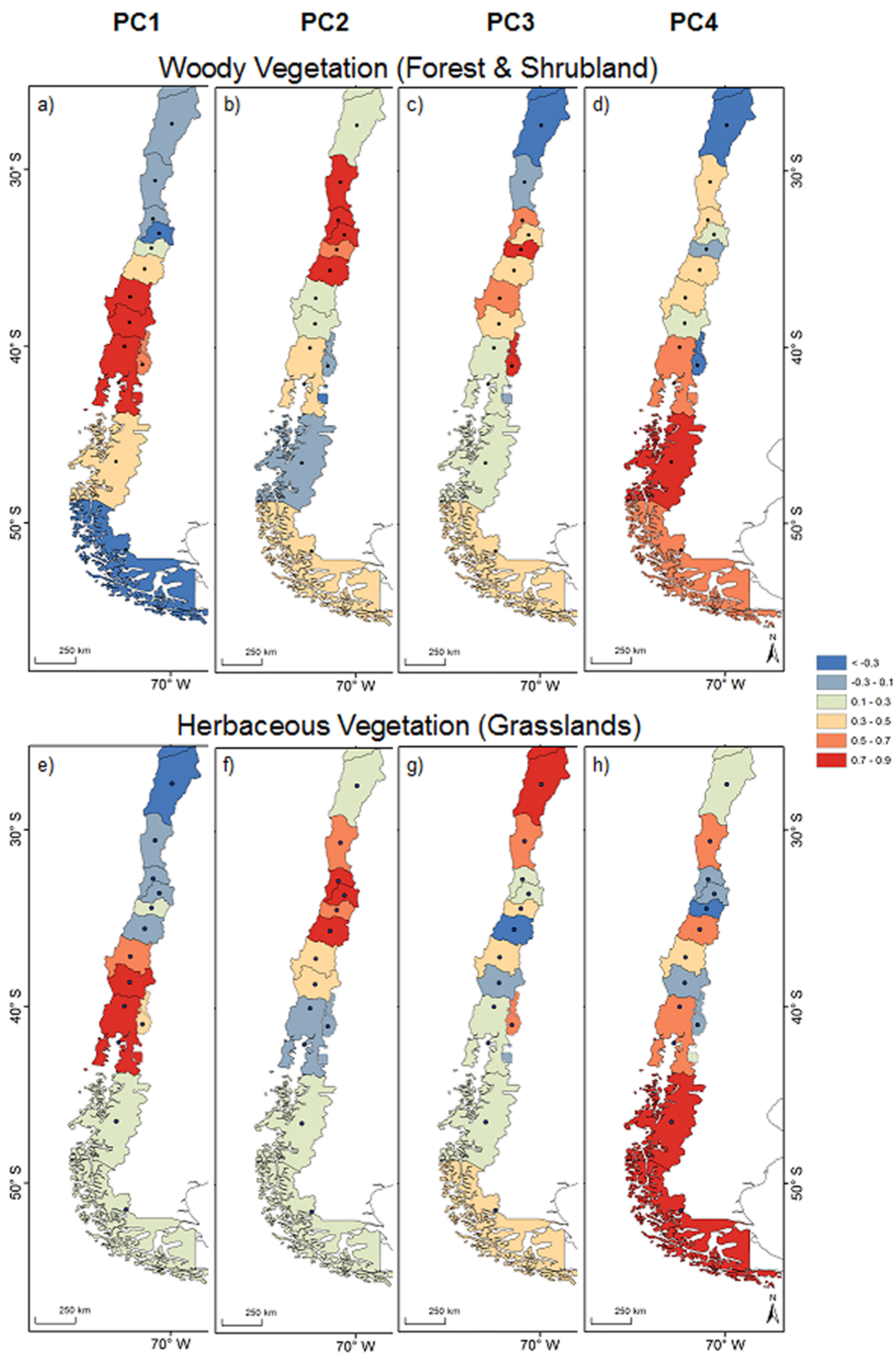

Fig. 4. Spatial patterns of the loadings of the first four PCs of annual area burned (AAB) in woody (forest and shrubland; a–d) and herbaceous (grasslands; e–h) vegetation during the 1984–2008 period. The main bioclimatic zones represented by each PC are roughly: (a) warm-wet Temperate zone, (b) Mediterranean zone, (c) Mediterranean zone and dry Temperate zone , and (d) cool-wet Temperate zone. High and low loading values are displayed in red and blue, respectively.

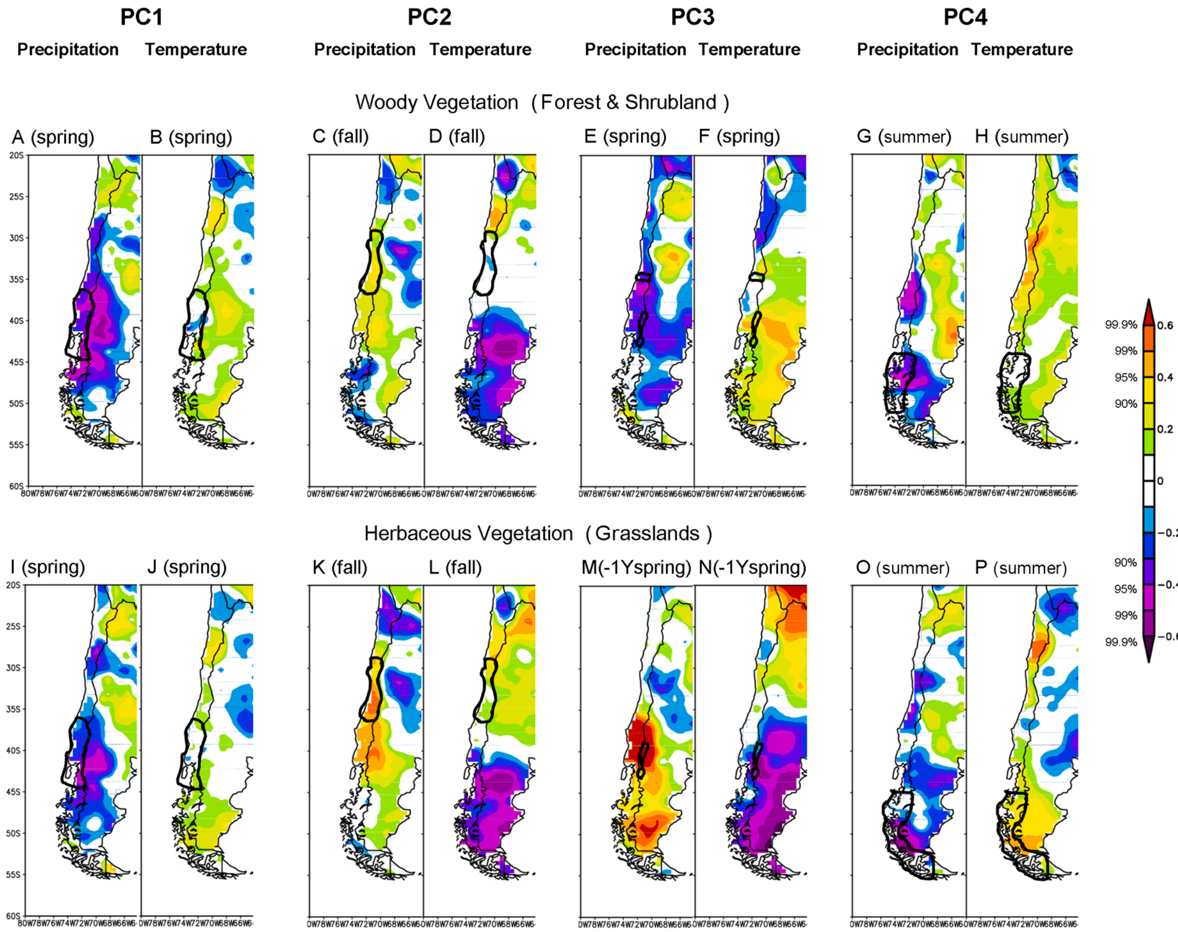

Fig. 5. Spatial correlations among the first four PCs of annual area burned (AAB; PC1, PC2, PC3 and PC4) in woody vegetation (forest and shrublands; a–f) and herbaceous vegetation (grassland; g–j) and seasonal surface precipitation and surface air temperature grids during the 1984–2008 period. Gridded climate dataset is from University of Delaware. Significant levels for correlation (and CI%) values are listed under the key. Seasons are fall (Mar–May), winter (Jun–Aug), spring (Sep–Nov), and summer (Dec–Feb). Bold black line roughly delineates areas represented by each PC.

PC2 scores (representing increased fire in woody vegetation in the Mediterranean zone) were positively correlated with precipitation during the fall of the year of fires (i.e., 3 to 9 months prior to the fire season) but were not significantly correlated with temperature (Fig. 5c, d). Fall precipitation in the Mediterranean zone was in turn negatively correlated with AAO (Fig. 6a), indicating higher than normal rainfall in this region when AAO is positive in the fall (Fig. 5c). High PC2 scores were related to stronger than average upper-level pressure at high latitudes and weaker than average upper-level pressure at mid-latitudes during the fall 3–9 months prior to the fire season (Fig. 7c). High PC2 scores were unrelated to any particular SST pattern in the eastern Tropical Pacific (Fig. 7d). Upper-level pressure ridges and troughs at mid-latitudes (30–45° S) are indicative of the negative phase of AAO resulting in increased precipitation in SSA (Fig. 6). This pattern represents a northerly shift of storm tracks in the SWW associated with higher than average upper-level pressure at high latitudes versus lower than average upper-level pressure at mid-latitudes (Fig. 7c). Thus, the association of higher AAB (represented by PC2) with the negative phase of AAO appears to reflect the effects of above

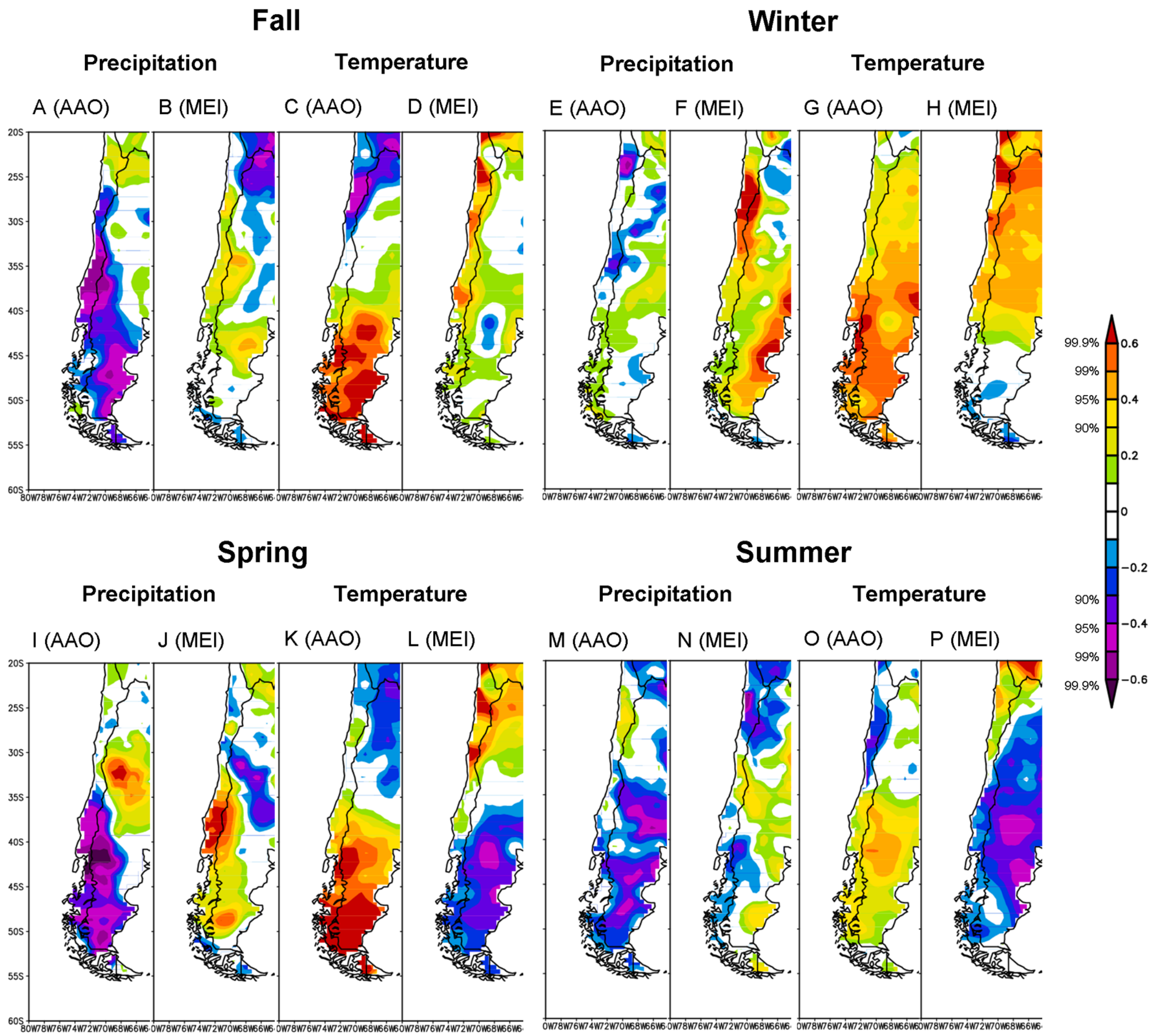

Fig. 6. Spatial correlations between indices of major climate drivers (AAO and MEI) and seasonal (and CI%) are listed under the key. Seasons are fall (Mar–May), winter (Jun–Aug), spring (Sep–Nov), and summer (Dec–Feb).

average precipitation during the fall of the current fire season. Note however, that while the area of increased precipitation spread from ca. 30–50° S, the area of increased fire activity was restricted to the Mediterranean bioclimatic zone ca. 30–37° S (Fig. 5c).

Variability in AAB expressed as PC3 (representing increased woody vegetation fires in the Mediterranean zone and dry Temperate zone) was found to be inversely correlated with precipitation during the spring of the fire year, and slightly positively correlated with spring temperature (Fig. 5e, f). Increased fire activity is associated with low rainfall in a northwest-to-southeast sector extending from the Mediterranean zone across the Andes showing a negative correlation with MEI reflecting la Niña conditions (Fig. 6j; Table 2). It is also associated with warmer summers that are positively correlated with AAO (Fig. 6k, o; Table 2). High PC3 scores are associated with high pressure centers over western and eastern mid-latitudes of SSA in the spring (Fig. 7e) and with cold tongue patterns of SSTs in the eastern Tropical Pacific Ocean, typical

Table 2. Direct and 1-yr lagged Pearson's correlation coefficients between PC1–4 loadings by vegetation type and seasonal climate modes (MEI, AAO). With 23 degrees of freedom, Pearson's correlation coefficients >0.51/<−0.51, >0.40/<−0.40, and >0.34/<−0.34 are significant at the 99%, 95%, and 90% confidence levels for two-level test, and in bold are ≥90% CI values. Seasons are: fall (Mar–May), winter (Jun–Aug), spring (Sep–Nov), and summer (Dec–Feb).

	Vegetation type							
	Woody				Herbaceous			
Current season	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
MEI								
Fall	0.15	0.2	0.05	0.03	0.22	0.16	0.28	0.06
Winter	0.07	−0.09	−0.31	0.29	0.12	0.08	−0.02	0.15
Spring	−0.02	−0.02	**−0.41**	0.28	0.01	0.20	−0.06	0.11
Summer	−0.02	0.05	**−0.38**	0.14	−0.04	0.28	−0.11	0.01
AAO								
Fall	−0.18	**−0.51**	0.07	0.23	−0.17	**−0.50**	0.22	0.003
Winter	0.02	0.26	0.13	0.33	0.16	0.20	0.15	0.23
Spring	**0.38**	−0.02	0.28	0.2	**0.43**	−0.12	0.02	0.26
Summer	**0.37**	−0.16	**0.35**	−0.03	**0.37**	−0.24	−0.09	0.03
Previous season								
MEI								
Fall	**−0.39**	0.23	0.23	0.06	−0.29	0.24	0.01	0.001
Winter	−0.04	0.21	0.33	−0.05	0.08	0.15	0.24	−0.19
Spring	0.11	0.20	0.28	0.07	0.28	0.07	**0.38**	−0.01
Summer	0.14	0.23	0.21	0.05	0.26	0.10	**0.39**	−0.01
AAO								
Fall	0.04	**−0.51**	0.11	−0.23	−0.03	**−0.41**	−0.25	−0.11
Winter	−0.02	−0.10	0.09	−0.27	0.07	−0.03	0.07	−0.19
Spring	−0.21	0.04	−0.06	−0.32	−0.14	0.17	**−0.44**	**−0.39**
Summer	−0.13	−0.32	−0.27	−0.31	−0.32	**−0.38**	−0.06	−0.09

of La Niña conditions (Fig. 7f). Unlike PC1, which is a spring-summer AAO-related pattern, PC3 is a combined La Niña and positive AAO pattern (Table 2).

Variability in AAB expressed as PC4 (representing increased fire in woody vegetation in the cool-wet Temperate zone) was correlated with low summer precipitation during the fire season (Fig. 5g). Low summer rainfall was only weakly teleconnected with positive AAO and with a positive MEI (El Niño) phase (Fig. 6m, n). The highest correlations of PC4 scores with seasonal climate modes were with winter-summer MEI and winter AAO, but did not reach statistical significance (Table 2); likewise, PC4 did not significantly correlate with low precipitation or high temperature during winters (not shown). However, PC4 scores were strongly correlated with a summer pattern of four well developed high and low pressure cells juxtaposed across the southeastern Pacific Ocean with a high pressure cell centered off the SW corner of southernmost SSA (Fig. 7g).

Herbaceous vegetation.—Similarly to woody vegetation fires, the spatiotemporal variability of PC1 for herbaceous vegetation fires was negatively correlated with spring precipitation, with little influence of other seasons or temperature (Fig. 5i). In turn, low precipitation during the spring was strongly correlated with positive spring AAO (Fig. 6i), which was also correlated with PC1 scores during spring and summer (Table 2). High PC1 scores were related to a weaker than normal upper-level pressure center at high-latitudes during the spring and a circumpolar band of stronger than normal upper-level pressure at mid-latitudes, typical of the positive phase of the AAO (Fig. 7i). Similar to woody vegetation fires, positive correlations of grassland AAB (represented by PC1) with spring AAO suggests below average precipitation associated with strong blocking events at mid-latitudes and a southerly shift in storm tracks.

As with woody vegetation fires, variation in grassland AAB expressed as PC2 (i.e., increased fires in the Mediterranean zone) was positively correlated with fall precipitation (Fig. 5k), which in turn was mostly driven by negative fall AAO over this region (Fig. 6a), with little influence of temperature variability (Fig. 5l). PC2 was nega-

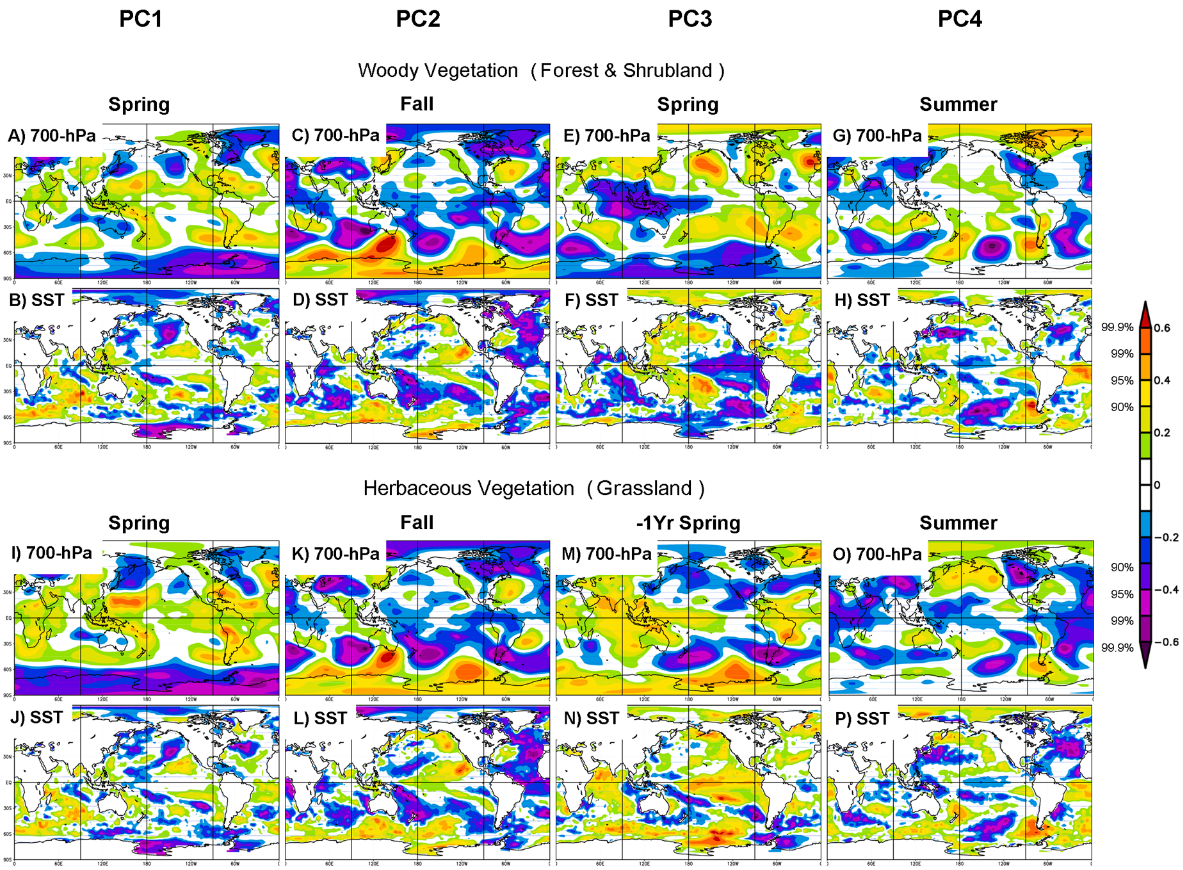

Fig. 7. Spatial correlations between first four PCs of annual area burned (AAB; PC1, PC2, PC3 and PC4) in woody vegetation (forest and shrublands; a–h) and herbaceous vegetation (grassland; g–j) and seasonal 700 hPa geopotential height (top panel) and seasonal SST (bottom panel) during the 1984–2008 period. The ocean/atmospheric dataset is from the NCEP-NCAR Reanalysis. Levels for correlation values (and CI%) are listed under the key. Seasons are fall (Mar–May), winter (Jun–Aug), spring (Sep–Nov), and summer (Dec–Feb).

tively correlated with fall AAO during the year of the fire (Table 2). The relationship between PC2 and negative AAO is clearly represented by blocking high-pressure at high-latitudes and low pressure at mid-latitudes (Fig. 7k). This pattern would be expected to favor above normal fall precipitation in the Mediterranean zone resulting from a northerly shift of the storm track (SWW).

Most of the variability in AAB expressed as PC3 (mostly representing increased grassland fire in the dry Temperate zone) was positively correlated with spring precipitation during the previous year (Fig. 5m). High spring precipitation in this region seems to be best explained by negative AAO (Fig. 6i; Table 2). Negative AAO is associated with the development of weaker than average upper-level pressure at mid-latitudes and stronger than average upper-level pressure at high latitudes the year prior to the fire year (Fig. 7m).

Variation in AAB expressed as PC4 (indicative of increased grassland fires in the cool-wet Temperate zone) was correlated with summer drought and above average temperatures during the fire season (Fig. 5o, p). Summer droughts (mostly negative rainfall anomalies) in this region are mostly related to positive AAO (Fig. 6m). Scores of PC4 however, were not significantly correlated with indices of large-scale climate drivers (Table 2). Nonetheless, summer droughts that favored high PC4 scores coincided with both a high-pressure cell off the southwestern coast of SSA interrupting zonal flow and with warmer air temperatures associated with warm SSTs in the same area (Fig. 7o, p).

Discussion

Fire activity along the latitudinal moisture gradient

Fire activity across the north-to-south latitudinal gradient of aridity/productivity exhibited the expected pattern with maximum values towards the center and with lower fire activity associated with extremes of moisture availability (Fig. 2). Maximal relative fire activity (i.e., mean area burned relative to the available area in each administrative district) was centered between the Mediterranean and warm-wet Temperate zones (ca. 32–40° S), where average climate is suitable for accumulation of sufficient biomass to burn and dry weather desiccates fuels annually (Fig. 8). During 1984–2008, the latitudinal belt from 32 to 40° S, representing less than 30% of the total gradient, accounted for ca. 50% of the relative area burned. At the arid northern extreme, low net primary productivity results in less total burnable biomass and in less spatially continuous fuels so that there is less fire activity despite frequent fuel-drying weather. Southwards of ca. 40° S median values of relative areas burned gradually decline to a nadir at ca. 52.5° S reflecting the infrequency of fuel desiccating weather in this region of abundant burnable biomass. The high variances in annual areas burned in the area south of 40° S (Fig. 2) are consistent with the dependence of fire activity on infrequent drought. The pattern of fire activity along the latitudinal moisture gradient generally fits the varying constraints hypothesis of Krawchuk and Moritz (2011) that explicitly considers spatial gradients in the relative importance of biomass versus fuel moisture constraints on fire activity. However, small differences in the rate of change in relative area burned along the latitudinal gradient undoubtedly reflect other factors such as human population densities, differential effectiveness of fire suppression, relative frequencies of human-set fires versus lightning ignitions, extent of plantations of exotic trees, and land-use legacies such as the amount of anthropogenic burning prior to the 1984 analysis period. These local influences on fire activity were beyond the scope of our broad-scale study and would require more detailed sub-regional analyses incorporating information on human impacts and potential feedbacks from prior burning (e.g., Mermoz et al. 2005).

Interannual patterns of fire activity

Along the extensive latitudinal gradient from arid ecosystems through seasonally dry to moist bioclimatic zones in SSA the coarse-scale pattern of annual variability in wildfire activity is controlled primarily by interannual climate variability as modulated by vegetation types and associated fuel characteristics. More than half of the variance in AAB is represented by two dominant modes of variability in AAB correlated in different ways with the Antarctic Oscillation, which is the main extra-tropical mode of climate variability over the Southern Hemisphere (Garreaud et al. 2009). The first mode of variability (PC1) reflects synchrony of fire in woody and herbaceous vegetation types at mid-latitude (ca. 37–42° S); this pattern is positively correlated with spring AAO which in turn is correlated with reduced spring precipitation (Fig. 6i). This region primarily coincides with temperate deciduous forests and woodlands where fire is not limited by fuel amount and is strongly associated with reduced spring precipitation resulting in low fuel moisture levels during the summer fire season. Increased fire activity during positive phases of AAO and associated drier conditions is also evident in multi-century tree-ring reconstructions of fire activity and of the AAO index for the same region (Holz and Veblen 2011).

The second mode (PC2) reflects synchronous fire in woody and herbaceous vegetation across the Chilean Mediterranean region (30–35° S) which is negatively correlated with fall AAO. Although anomalous rainfall in central Chile is well known to be linked to El Niño events and a weak SE Pacific subtropical anticyclone (Rutllant and Fuenzalida 1991), recent studies have found strong correlations between the intensity of the SE Pacific subtropical anticyclone and AAO (Quintana and Aceituno 2012). Specifically, aridity along the subtropical west coast of South America has been related to high-latitude forcing linked to AAO (Vuille and Milana 2007). This is consistent with our findings emphasizing the importance of AAO as a driver of fall precipitation and lagged fire activity. Again, as for the first mode of variability, vegetation type modulates

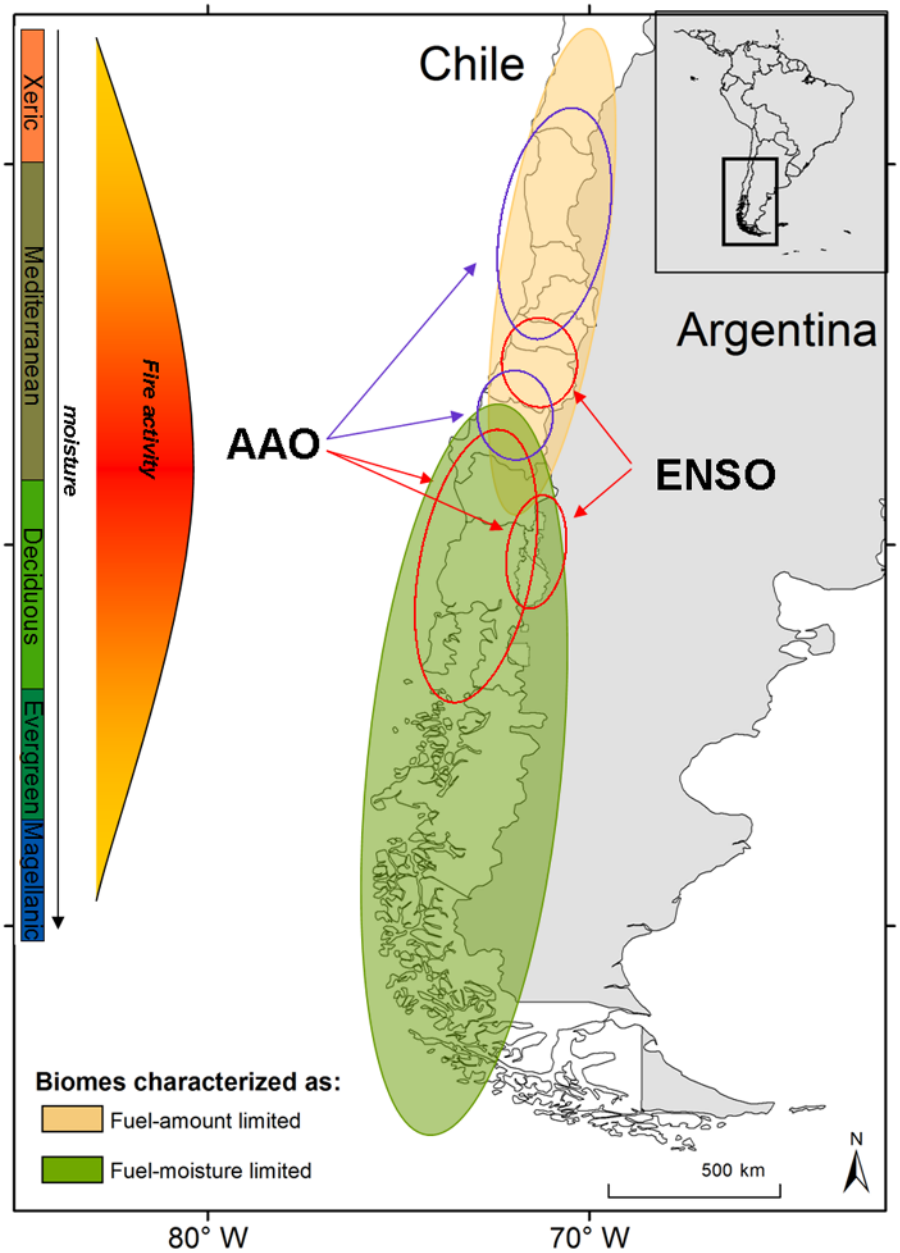

Fig. 8. Summary of the influences of interannual climate variability driven by variability in AAO and ENSO as ecological constrained by fuel properties of different biomes in SSA from xeric scrubland in the north to wet Magellanic forests in the south. Interannual climate variability include effects on both fine fuel production and fuel desiccation. Teleconnections to AAO and ENSO may either increase precipitation (blue arrows and ovals) and build-up of fuels (area in orange) and/or may decrease precipitation (red arrows and ovals) and desiccate fuels (area in green).

the fire-climate relationship. To wit, only regions dominated by Mediterranean-type shrublands and grasslands exhibit increased fire activity despite the distribution of enhanced fall precipitation during negative AAO phases across a much broader latitudinal band (30–45° S). This suggests that only Mediterranean-type fuel-limited ecosystems respond to increased fall precipitation with more fire, whereas fire did not increase in the more fuel-rich forests southwards when fall precipitation also increased. This is another example of how different vegetation types modulate fire-climate relationships so that climate variability alone is not sufficient to predict future fire activity (Hessl 2011, Gartner et al. 2012, Pausas and Paula 2012).

The broad-scale quantitative analyses of fire-climate relationships in the current study are consistent with qualitative observations that in Mediterranean shrublands of central Chile fire risk increases following wet autumns, winters and springs due to increases in abundance of herbaceous biomass followed by typically dry summers that desiccate fine fuels (Montenegro et al. 2004, Quintanilla 2009). Similarly, antecedent moist conditions are reported to favor subsequent fire activity through enhanced production of herbaceous fuels in the coastal area of California's (USA) Mediterranean-type climate (Keeley 2004). In contrast, in chaparral-dominated ecosystems in a smaller area in southern California, antecedent climate conditions and herbaceous fuel quantities were found to be unimportant in predicting fire extent relative to the strong role played by low fuel moisture during the fire season (Dennison and Moritz 2009). Such contrasts highlight the probable importance of sub-regional differences in relative amounts of grasslands, savanna-like woodlands, and dense chaparral-type shrublands as well as the variable role played by strong foehn winds within a region of relatively homogeneous climatic variability in a Mediterranean-type biome.

The remaining two PC modes together explained one fourth of the variance in AAB. One of these modes (PC3) links fire activity in some districts of central Chile with mid-latitude districts on the eastern Andes in Argentina. Woody fuel fire activity is related to below normal spring precipitation associated with a contingent state of positive AAO and negative phase of ENSO (La Niña). Previous tree-ring based research on fire in the Argentinean Lake district has documented influences of both ENSO variability and high latitude climatic patterns related to AAO (Kitzberger and Veblen 1997, Kitzberger 2002, Veblen and Kitzberger 2002). However, the contingent action of ENSO and AAO as reflected in the PC3 mode is only recently starting to be considered in tree-ring studies of fire history, which also relate enhanced fire activity to periods of coincident cool ENSO phases and positive AAO phases (Veblen et al. 1999; Mundo et al., *in press*). These findings are consistent with recent advances in climate science showing the strength of high latitude ENSO teleconnection in the South Pacific is contingent on AAO (Fogt et al. 2011).

Grassland fires generated a different pattern from woody fuel fires reflected in the PC3 mode (Fig. 4c). Higher spring precipitation associated with the warm phase of ENSO (El Niño) was followed a year later by increased burning of grassland vegetation. On the easternmost flanks of the Argentinean Lake district, extensive grasslands develop across the Patagonian Plateau. Overgrazing by sheep and overall dry conditions make this a fuel-limited ecosystem that requires as in similar semiarid systems $>50\%$ plant cover to spread fire (Morgan et al. 2003). Growing season rainfall pulses one year previous to the fire season increase annual grass cover (Jobbágy and Sala 2000) and enhance fire spread conditions and fire frequency (Kitzberger et al. 1997). We found this same lagged relationship in the arid northern Chilean districts (1-AR, 2 CQ) where ENSO-related rainfall pulses produce large increases in grass cover and productivity (Gutiérrez et al. 2000). A lagged influence of increased moisture influences on fire activity is a common pattern in fuel-limited semiarid regions (O'Donnell et al. 2011). The last mode of variability (PC4) encompasses fire activity restricted to the Temperate/Sub-Antarctic region characterized by relatively evenly distributed precipitation throughout the year. While statistical relationships with indices of climate modes were not significant (Table 2), there is a spatial association of PC4 with reduced summer precipitation, which is generated by blocking anticyclones over the southern tip of South America. In this zone, fire is promoted during drier than normal summers through a teleconnection trends with the warm phase ENSO and positive AAO during years of above average fire occurrence.

Our analyses of fire-climate relationships show that variability in fire activity over the past quarter century along the latitudinal gradient in SSA appears to be primarily controlled by the position and intensity of the SWW as forced by the pattern of AAO and secondarily (or contingently) by ENSO variability. The current study, by having a larger geographic coverage than previous analyses of fire history in SSA provides a more comprehensive understanding of how the influences of large-scale climate patterns on fires vary over a sub-continental region. A potential limitation to our findings is uncertainty about the long-term stationarity of teleconnections of local climate variability to climate modes such as ENSO and AAO. Consequently, it is important to complement analyses based on the relatively short documentary record of fires with longer-term tree-ring based records of fire and reconstructions of climate modes (e.g., Holz and Veblen 2011, 2012; Mundo et al., *in press*) and integrate the findings with millennial scale studies based on charcoal records (Whitlock et al. 2007, Moreno et al. 2010). In addition, despite the limitation of the relatively short 25-year fire dataset, the broad range in timescales at which AAO accurately predicts weather patterns (i.e., from 10 days to annually; Thompson and Wallace 2000) is reason for confidence in the stationarity of our seasonal analysis of the variability in the AAO and its teleconnection to climate variability and wildfire.

Our results emphasize the importance of vegetation type and associated fuel characteristics in shaping fire-climate relationships along the extensive latitudinal moisture gradient of SSA. Average climate through its control of biomass available to burn results in differential consequences of the effects of interannual climate variability on fine fuels and fuel moisture manifested as differential responses of wildfire activity to the same climatic signal over large regions at scales on the order of 100,000 km^2 (Fig. 8). Despite the similarity of climate anomalies across the mid-latitudes of SSA forced by variations in AAO (Vuille and Milana 2007, Garreaud et al. 2009, Quintana and Aceituno 2012), different mechanisms generated diverse and spatially-segregated responses of wildfire activity. In the moisture limited, biomass-poor ecosystems of the Mediterranean zone of central Chile, fire occurrence depends largely on preceding anomalous high precipitation that induces fine fuel build-up; it depends less on anomalous fuel desiccation during the spring-summer season, which is consistently dry in the Mediterranean climate (Fig. 8). Therefore, somewhat paradoxically, fire activity in this region is related to a weakened rather than a strengthened SE Pacific subtropical anticyclone. In contrast, in biomass rich forest ecosystems, such as the seasonally dry forests of south-central Chile and the Argentine Lake District, fuel amount is not limiting but years in which fuels dry sufficiently for easy fire spread are relatively rare (Fig. 8). In these ecosystems, the influence of AAO reverses so that positive AAO phases (in conjunction with ENSO) are associated with a strengthened SE Pacific anticyclone and drought conditions during spring which generate increased fire activity.

Comparable to our findings for SSA, across the similar latitudinal gradient from northwestern Mexico to southeast Alaska, the effects of variations in major climate modes on fire activity are also modulated by vegetation type (Gedalof et al. 2005, Littell et al. 2009). For example, in semi-arid ecosystems in the southwestern U.S. where fire activity is constrained by fuel amount, increased fire activity lags by one year above average moisture related to the El Niño-enhanced precipitation followed by same year drought related to dry La Niña conditions (Swetnam and Betancourt 1990, Swetnam and Betancourt 1998). In contrast, in productive rainforests of the Pacific northwest, fire primarily depends on same year drought conditions, generally related to warm El Niño phase (Gedalof et al. 2005). Thus, the climatic see-saw pattern of rainfall and ENSO between the southwestern and northwestern U.S. (Kitzberger et al. 2007) also incorporates modulating effects of the vegetation on fire activity. Further north in southern and central Canada, positive phases of the Arctic Oscillation (AO; the equivalent annual pattern to the AAO in the Northern Hemisphere) enhance fire activity at mid-latitudes by expanding the influence of mid-latitude blocking highs whereas negative AO enhances fire at higher latitudes due the southward expansion of the Arctic blocking high (Macias Fauria and Johnson 2006).

In conclusion, our results underscore the importance of considering the role of vegetation type in modulating the effects of coarse scale climatic variability on fire activity. While large scale climate drivers produce relatively coarse teleconnection patterns, vegetation differences (sometimes even within the same biome) act as a finer filter determining the nature of climate-fire relationships that are important for effective fire hazard mitigation and planning. Furthermore, our findings are consistent with global modeling approaches that predict fire activity from long-term average climate conditions (e.g., Krawchuk et al. 2009, Pechony and Shindell 2010), but our results also suggest that greater explanatory power can be gained from incorporating interannual variability in climate. Predictions of future fire activity based on long-term climate norms and scenarios of future climate from General Circulation Models recognize the uncertainty associated with interannual climate variability and its consequences for fire activity (Moritz et al. 2012). Our findings for SSA also imply that long-term global fire projections could be improved by developing reliable projections of interannual climate variability. The current decades-long positive trend in AAO is increasingly being identified as the key driver controlling climate trends (Miller et al. 2006, Thompson et al. 2011) and climate-dependent ecological processes (Murúa et al. 2003, Holz and Veblen 2011, Paritsis and Veblen 2011) over a large part of the temperate latitudes of South America. Our study provides an initial understanding of how climate trends related to AAO variability differentially affect wildfire activity across the major vegetation types of SSA which will inform studies of future fire potential incorporating both average climate and interannual variability.

Acknowledgments

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Supplemental Material

Appendix A

Table A1. Estimated cover (%) of the main vegetation types in each of the administrative districts analyzed in this study.

					Vegetation type†		
					Native		Exotic
Bioclimatic zone‡	Administrative district	Code	Latitude (°S)	Total area (ha × 10^6)	Forest and shrubland (%)	Grassland (%)	Tree plantation (%)
Mediterranean	Atacama	1-AT	26–29	7.9	<1	34	0
	Coquimbo	2-CQ	29–32	3.8	51	34	<1
	Valparaíso	3-VA	32–33	1.6	77	19	4
	Metropolitana	4-RM	33–34	1.7	73	27	<1
	O'Higgins	5-OH	34–35	1.6	86	17	7
	Maule	6-MA	35–36	2.9	61	19	20
Mediterranean/ Temperate	Bio-Bio	7-BI	36–38	3.8	60	7	33
Temperate	Araucanía	8-AR	37–40	3.1	30	19	18
	Los Ríos	9-RI	40–41	1.8	48	30	10
	4 National Parks (Argentina)	10-NP	39–43	1.4	86	5.4	<1
	Los Lagos	11-LA	41–44	4.8	95	4	1
	Aysén	12-AY	44–49	10.4	59	20	<1
	Magallanes	13-MG	49–53	9.4	66	22	<1
Temperate/Sub-Antarctic	Magallanes	13-MG	53–54	1	86	13	<1
Sub-Antarctic§	Magallanes	13-MG	54–56	2.8	84	4	<1

† Cover (%) of the main vegetation type are from (CONAF, *unpublished report*) and WWF Ecoregion Map (Lara et al. 1999).
‡ Bioclimatic zones follow Amigo and Ramírez (1998).
§ We used the name "Sub-Antarctic" instead of "Boreal" that was originally suggested by Amigo and Ramírez (1998).

Appendix B

Although in both countries the AAB record starts earlier (ca. 1943 in Argentina and ca. 1964 in Chile), and in AAB Chile is currently differentiated by each individual dominant vegetation type (i.e., forest, shrubland, and grassland), we used AAB for forest and shrublands combined, and for grassland for the 1984–2008 period due to (a) in Chile the AAB record prior to the 1976–77 year is not considered reliable outside the Central Valley (CONAF; *personal communication*), (b) in Chile the AAB record differentiates by individual vegetation types starting only in the 1984–1985 fire season, (c) in Argentina the AAB record differentiates by individual vegetation types starting only in the 2000–2001 fire season (previously, it combined AAB in forest and shrubland), and (d) in Argentina the AAB record after 2008–2009 stopped being reliable (APN; *personal communication*).