Clim. Past Discuss., 7, 3203–3238, 2011
www.clim-past-discuss.net/7/3203/2011/
doi:10.5194/cpd-7-3203-2011

Climate of the Past Discussions

Fire history in western Patagonia from paired tree-ring fire-scar and charcoal records

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Received: 2 September 2011 – Accepted: 22 September 2011 – Published: 10 October 2011

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Fire history reconstructions are typically based on tree ages and tree-ring fire scars or on charcoal in sedimentary records from lakes or bogs, but rarely on both. In this study of fire history in western Patagonia (47–48° S) in southern South America (SSA) we compared three sedimentary charcoal records collected in bogs with tree-ring fire-scar data collected at 13 nearby sample sites. We examined the temporal and spatial correspondence between the two fire proxies and also compared them to published charcoal records from distant sites in SSA, and with published proxy reconstructions of regional climate variability and large-scale climate modes. Two of our three charcoal records show fire activity for the last 4ka yrs and one for the last 11 ka yr. For the last ca. 400 yr, charcoal accumulation peaks tend to coincide with high fire activity in the tree-ring fire scar records, but the charcoal records failed to detect some of the fire activity recorded by tree rings. Potentially, this discrepancy reflects low-severity fires that burn in herbaceous and other fine fuels without depositing charcoal in the sedimentary record. Periods of high fire activity tended to be synchronous across sample areas, across proxy types, and with proxy records of regional climatic variability as well as major climate drivers. Fire activity throughout the Holocene in western Patagonia has responded to regional climate variation affecting a broad region of southern South America that is teleconnected to both tropical- and high-latitude climate drivers – El Nino-Southern Oscillation and the Southern Annular Mode. An early Holocene peak in fire activity pre-dates any known human presence in our study area, and consequently implicates lightning as the ignition source. In contrast, the increased fire activity during the 20th century, which was concomitantly recorded by charcoal from all the sampled bogs and at all fire-scar sample sites, is attributed to human-set fires and is outside the range of variability characteristic of these ecosystems over many centuries and probably millennia.

1 Introduction

Fire is increasingly recognized as a keystone disturbance process in southern South America (SSA) (Veblen et al., 2003, 2011; Whitlock et al., 2007). However, the relative contribution of deliberate burning by prehistoric peoples versus control primarily by regional climate variation remains uncertain and controversial (Heusser, 1994; Markgraf and Anderson, 1994). Different interpretations of the contributions of humans to fire history variability may reflect the coarse spatial and temporal resolution at which most records of fire and land use have been examined. The goal of the current study is to improve our understanding of fire history reconstructions by comparing long-term, sedimentary charcoal with nearby fire-scar chronologies in temperate rainforests in western Patagonia (Fig. 1).

In southern South America, fire history reconstructions commonly have been based on two approaches: (a) dendrochronological dating of fire scars and stand ages (Veblen and Lorenz, 1987; Kitzberger and Veblen, 1997), and (b) dating of charcoal from sedimentary records from lakes or bogs (Heusser, 1987; Whitlock and Anderson, 2003). Each of these techniques has unique strengths and weaknesses: tree-ring studies have annual (and sometimes even seasonal) temporal resolution and usually have an easily specified spatial resolution. However, the fire-scar records are typically only robust over a few centuries and rarely can reliably capture changes in fire activity beyond a millennium. In contrast, charcoal-based fire history reconstructions can extend back for millennia, but in general have comparatively poor temporal resolution (typically supra-decadal resolution) that impedes analyses of fire variability related to interannual scale variability in climate drivers such as ENSO. The spatial extent of burning associated with a charcoal sedimentary record also may be difficult to determine (Whitlock and Anderson, 2003). Although the combined use of these two proxy types may provide complementary information and can improve interpretation of past fire activity, such studies are relatively uncommon (Clark, 1990; Whitlock and Anderson, 2003; Allen et al., 2008; Higuera et al., 2010a).

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Fire history research in southern South America (SSA) based on short-term documentary fire records, tree-ring reconstruction of fire, and sedimentary charcoal records are all contributing to an improved understanding of how variability in major climate drivers affect regional climate variability and in turn wildfire activity. In northern Patagonia in Argentina (39–42° S), both documentary fire records (post-1937) and multi-century tree-ring fire records of fire reflect strong ENSO influences on fire (Kitzberger and Veblen, 1997, 2003; Veblen et al., 1999; Kitzberger, 2002; de Torres Curth et al., 2008). Similarly, in south-central Chile (39° S) tree-ring reconstructed fire history over the past several centuries is significantly related to ENSO (González and Veblen, 2006). Likewise, changes in fire regimes derived from charcoal and pollen records in the middle to late Holocene over a broad area of Patagonia have been related to the onset and subsequent intensification of ENSO at ~6 and/or ~3 ka (Whitlock et al., 2006; Abarzua and Moreno, 2008; Moreno et al., 2010). Variability in high-latitude circulation patterns related to the latitude and strength of the southern westerly winds (SWW) is also reflected in interannual to millennial-scale variability in wildfire activity in SSA (Veblen et al., 1999; Whitlock et al., 2007). For example, analyses of tree-ring fire history records from 42 to 48° S related wildfire activity to variability in the Southern Annular Mode (SAM) which is the principal extratropical driver of climate variability in the southern hemisphere (Holz and Veblen, 2011). Furthermore, when tropical sea surface temperatures are in a warm phase, the fire-enhancing influence of positive SAM in western Patagonia is intensified (Holz and Veblen, 2011a). Similarly, analyses of post-satellite era (1979–2003) climate patterns indicate that intensities of regional climate teleconnections to either ENSO or SAM are contingent on phases of both drivers (Pezza et al., 2008).

Holocene patterns of fire derived from spatially coarse-scale charcoal records reveal some regionally consistent patterns most likely related to major climate shifts (Whitlock et al., 2007). These include increased burning in the early Holocene as a result of warming conditions at the end of the glaciations and possible weakening and southward shifts in storm tracks. Latitudinal differences in fire patterns in the middle Holocene imply increased summer precipitation at mid-latitudes (Whitlock et al., 2007). However, regionally variable fire activity in the late Holocene may reflect either increased interannual to inter-decadal climate variability related to ENSO or increased burning by Native peoples or both. Improved understanding of the causes of this variability, especially in the late Holocene, requires a more complete network of charcoal and tree-ring fire records as well as better resolved records of pre-historic human activities. We base our interpretation of charcoal and fire-scar records from western Patagonia on new reconstructions of archaeological and ethnohistorical records of human activities in western Patagonia (Holz and Veblen, 2011b) as well as proxy records spanning most of the Holocene of the position and strength of the SWW (Lamy et al., 2010) and of ENSO (Moy et al., 2002; Koutavas and Sachs, 2008).

Previous charcoal and tree-ring fire histories in SSA are for locations in central, south-central Chile and northern Patagonia at 34–46° S (Heusser, 1983; Moreno, 2000; Whitlock et al., 2006; Markgraf et al., 2007, 2009; Abarzua and Moreno, 2008) or in the far south of Patagonia and Tierra del Fuego at 51–55° S (Huber and Markgraf, 2003; Huber et al., 2004). For western Patagonia to the windward side of the Andes south of 42° S there is only one published charcoal record at 44° S (Haberle and Bennett, 2004), and there are no charcoal records in western Patagonia from 46 to 51° S. In the present study, we use paired records of charcoal and tree-ring fire histories to examine variability in Holocene wildfire activity at 47 to 48° S in western Patagonian rainforests. Our primary objectives are to compare fire records derived from sedimentary charcoal with nearby tree-ring fire records, and to evaluate the reliability of inferring fire activity from bog charcoal records alone. To attain these objectives, we: (a) developed long term charcoal records from 3 newly sampled bogs, and (b) compared the temporal and spatial correspondence between these charcoal records with nearby tree-ring reconstructed fire histories (Holz and Veblen, 2011b). Finally, we compare our findings for western Patagonia with published proxy reconstructions of regional climate and of broad-scale climate drivers as well as records of local pre-historic and historic human presence and land use (Holz and Veblen, 2011b).

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2 Material and method

2.1 Sampling sites

2.1.1 Study area

Records of wildfire activity were produced by sampling sedimentary charcoal at three bogs and fire-scarred trees at 13 sample sites located in the Baker, Bravo, and Quetru-Pascua rivers watersheds (Fig. 1; Tables S1 and S2 in the Supplement; detailed information on the fire-scar records are in Holz and Veblen, 2011b). Sediment cores were collected using an 80mm diameter by 1m long piston corer at the Casanova (MCa) and Tortel (MTo) bogs (hereafter *mallines*) in the Baker river watershed, and at the Leal *mallín* (MLe) in the Bravo river watershed. At and nearby these three sediment sampling sites, a total of 13 bog forest or *mallín* sites were sampled for tree-ring fire scars; sample areas varied in size from ca. 10 to 120 ha (Fig. 1; Table S1 in the Supplement). All sediment and fire-scar sample sites are characterized by acidic and poorly drained soils as is common for Pilgerodendron forests (Pilgerodendron uviferum (D. Don) Florín (Guaitecas Cypress; Lara et al., 2006), the dominant tree species at all sites. Pilgerodendron inhabits ecotonal areas between well drained forested sites and valley bottom *mallín* sites characterized by *mallín* and cushion species (e.g. Sphagnum spp., Astelia spp. and Donatia spp.). In well drained forests, Pilgerodendron mainly co-occurs with the broadleaved evergreen Nothofagus betuloides in our study area (Lara et al., 2006).

The study area is characterized by a west coast marine climate with relatively uniformly distributed precipitation and temperate conditions (Garreaud et al., 2009). Annual precipitation ranges from ca. 2000 to 4000 mm at sea level, increases with elevation (Garreaud et al., 2009). In the case that our sample areas had asynchronous fire peaks, the topographic and climatic characteristic of our study area were suitable for disentangling high versus low human impact on fire activity. The study area is characterized by rugged, glacial topography (Niemeyer et al., 1984) providing topographic barriers to charcoal dispersal. Pilgerodendron ecosystems are characterized

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by variable severity fire regimes (also known as mixed severity) in which both surface and crown fires occur (Holz and Veblen, 2009). In tall forests on better drained sites that are dominated by Pilgerodendron, fire scars and cohort age structures indicate that fires are of high severity (i.e., crown fires). In adjacent bog forests, surface fires occur more frequently, and at least some of these fires are not lethal to Pilgerodendron (Holz, 2009). Fire in the tall forests is dependent on more extreme drought than in the *mallín* vegetation where fine fuels are more easily desiccated.

2.2 Sample processing and analyses

2.2.1 Sediment records

Sediment cores where initially scanned through a Barrington Magnetic susceptibility loop at 1cm intervals. This enabled us to identify mineral magnetic inputs associated with volcanic tephras or inwash events. The sediment cores were then sectioned in contiguous 1 cm samples for charcoal analysis and involved wet sieving 2 cm^3 samples through 125 and 250-micron sieves, lightly bleaching the coarse fraction in sodium hypochlorite (6 %) and counting black particles under a binocular dissecting microscope. Very low counts in the >250 micron category meant that the data was combined into one size class of >125 microns and expressed as a concentration of particles per cm^3.

2.2.2 Development of an age model

Chronological control of the record was provided using ^{14}C dating of charcoal present in the cores. Charcoal was chemically cleaned by a series of HCl (1N) and NaOH (1N) baths at 80 °C to remove secondary carbon deposits, exposing the original structural carbon lattice. The cleaned charcoal (~2 mg) was then sealed into quartz reactors under vaccum and combusted at 900 °C. The resulting CO_2 gas was then cryogenically trapped and purified in a vaccum line and converted to graphite using H_2 and iron oxide

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as a catalyst. The resulting graphite was then pressed into AMS target holders and analyzed at the KECK carbon cycle AMS facility of the University of California at Irvine. Radiocarbon ages are reported following the conventions of Stuiver and Polach (1977) and corrected for isotope fractionation using the AMS δ^{13}C measurement. Calibrated radiocarbon dates from sixteen sediment samples (8 for *mallín* Casanova, 4 for *mallín* Tortel and 4 for *mallín* Leal; Table S2 in the Supplement) were used to develop a linear age-depth model (see below).

2.2.3 Macroscopic charcoal analysis

Macroscopic charcoal recovered from peat deposits is thought to consist of two components: a slowly changing "background", which represents the slow integration of charcoal from regional fire events through the filter of catchment transport processes (Whitlock and Millspaugh, 1996; Marlon et al., 2006); and short-lived charcoal "peaks", which are thought to represent charcoal produced by fire events occurring within a relatively local scale, plus charcoal contributed through sedimentary and analytical noise (Higuera et al., 2007). In order to reconstruct fire history close to the coring sites, the macroscopic charcoal time series was first plotted on the age model described above, interpolated into 25-yr bins (the median resolution of the records), and then converted into charcoal accumulation rates (particles cm^{-2} yr^{-1}). The charcoal accumulation series was then decomposed into background and peak components using CharAnalysis (Higuera et al., 2009; freely available at: http://code.google.com/p/charanalysis/). Background charcoal was estimated by smoothing the charcoal time series to a 1000 yr window, using a locally weighted least squares regression robust to outliers. Residual charcoal values exceeding background levels were defined as the peak series. In order to distinguish "true" local fire events from noise-related variability in the peak series, we assumed that the peak series incorporates normally distributed variation around the background charcoal series (Gavin et al., 2006). In order to separate charcoal peaks from this noise, we used a Gaussian mixture model to estimate the mean and variance of the noise distribution. Fire events (hereafter CHARs) were identified as peaks

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exceeding the 99th percentile of the noise distribution. Finally, peaks were subject to a "minimum count test" which assesses whether a charcoal count identified as a peak has a >5 % chance being derived from the same population as counts for the previous five samples, assuming that charcoal counts are Poisson distributed around an unknown real value (Higuera et al., 2010b). In addition, Pearson correlation coefficients were computed between all CHAR records and background charcoals for the overall coinciding period to examine potential evidence of regional climatic controls on fire activity.

2.2.4 Fire-scar based fire history records

Fire-scar records were obtained exclusively from the species Pilgerodendron in bog forests and adjacent well drained sites at ~47–48° S in the rainforest district west of the Andes (see Holz, 2009). Five sample sites were located in the Baker and Quetru-Pascua watersheds, and three in the Bravo watersheds (Fig. 1). An average of 11 partial cross-sections (McBride and Laven, 1976) of fire scars were collected at each of the 13 Pilgerodendron sites, which yielded 4 to 8 cross-dated fire-scar samples per site (Table S1 in the Supplement). Cross-sections and cores were processed in the lab using standard dendrochronological techniques, including visual and statistical crossdating using COFECHA (Holmes, 1983). The crossdating process was conducted using existent (Roig and Boninsegna, 1990; Szeicz et al., 2000; Aravena, 2007) and newly developed Pilgerodendron tree-ring chronologies (Holz, 2009). According to convention for the southern hemisphere, years of annual rings and fire dates are assigned to the calendar year in which ring formation begins because the growing season extends across two calendar years (Schulman, 1956). The software program FHX2 (Grissino-Mayer, 1995) was used for graphing, filtering, and statistical analyses of the fire-scar data.

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2.3 Evaluating peat charcoal records and fire-scar records: detection and calibration

To examine the correspondence between fire records derived from CHAR and from tree-ring fire scars, we created several versions of the fire-scar fire history record based on varying filters of the number and percent of minimum trees per site and minimum sites per watershed recording fire in a given year. To graphically compare the temporal correspondence between the CHAR record and the fire-scar record within each watershed, we aggregated the fire-scar data from all sites and created a record of all fire years (i.e., minimum of only one scarred tree in each site) and another of widespread fire years (i.e., minimum of two trees scarred per site and at least 20 % of trees scarred in the study watershed). The 20 % filter better reflects the influence of climatic conditions on fire probability and fire spread (as it is based on synchronous fire occurrence in several trees sampled in all sites within each watershed). The metric of all fire years (i.e., no filtering) is inherently more sensitive to variability in the frequency of small fires and therefore will better capture changes in local fire activity recorded at each cored *mallín* as macroscopic charcoal peaks.

To assess spatial correspondence between the charcoal and the fire scar records, we examine the variation of the paired and more distant fire-scar sites from the cored *mallín* in each watershed. For this, we smoothed the fire-scar record using a 25-yr locally weighted scatterplot of smoothed means (Cleveland, 1979), since the CHAR records were interpolated to 25 yr intervals (see above). At each site, the smoothing process used different time periods specific to both all fire years (no filter) and for widespread fire years (20 % filter; Table S1 in the Supplement). Potential correspondence between the fire scar and charcoal records was examined using Spearman's rank correlation coefficients as follows. First, correlations were computed between the CHAR record and the smoothed percent of trees burned in each of the fire scar sites within the same watershed during all fire years (i.e., minimum of only one scarred tree in each site). Both the CHAR and the all year fire-scar records reflect the "most local" fire events. Second, correlations were computed between the background charcoal and the smoothed percent of trees burned in each of the fire scar sites within the same watershed during widespread fire years (i.e., minimum of two trees scarred per site and at least 20 % of trees scarred in a site). Whereas the background charcoal could also reflect local fires that coincided with a year of extensive regional fires, background charcoal and the strongly filtered fire scar record reflect extra-local fire events over extensive areas. Background charcoal could also reflect ongoing movement of charcoal into the depositional space (i.e., the *mallín*), where charcoal can lie around in the catchment and be slowly eroded or washed into the bog and become background charcoal. Additional correlations were computed between the background charcoals and the smoothed percent of trees burned in each of the fire scar sites within the same watershed during all fire years. The purpose of this was to test the assumptions related to CHAR and background charcoal. As explained above, in our analysis, a "charcoal peak" had to exceed the 99th percentile of the noise distribution. However, we also identified CHAR values that were above background levels even if they did not meet the 99th percentile criterion. These correspondence analyses are interpreted taking into account the potential influence of the prevailing winds and the rugged topography.

3 Results

3.1 Sediment stratigraphies and chronologies

From *mallín* Casanova we obtained a 3.5 m sediment core (Fig. 2a). For the interval encompassing the last ca. 6370 ± 20 yr BP years the sediment core consists of brown fibrous *mallín*, after which we found two layers of grey-brown silty clay (i.e. before and after ca. 7165 ± 25 yr BP). We found one tephra in the core (ca. 300–310 cm length) dated ca. 7165 ± 25 yr BP (Figs. 2a, 3), and it is believed to be derived from Volcán Hudson; correlating in time with H1 now dated at ca. 7500 yr BP (Charles R. Stern; personal communication, 15 August 2011) and with HW4 in the eastern Chonos Archipelago

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(Haberle and Lumley, 1998). A rather steady decrease in mineral magnetic inputs is observed from the top down of the record until the Hudson tephra (Fig. 2a), which is the major peak throughout the core. There are a few minor inwash events of magnetic minerals from the present through to ca. 3400 yr BP. We obtained a shorter core from the *mallín* Tortel (1.75 m sediment core; Fig. 2b). At the *mallín* Tortel we obtained a sediment core that consists of brown fibrous *mallín* encompassing the first 140 cm, with a brown organic-rich clayey silt below it until the end of the core. No tephras were found in this core. Minor fluctuations in mineral magnetic inputs were also found in this core, with minor increases in the present, ca. 1000 BP, and right before 2855 BP (Fig. 2b). From the *mallín* Leal, we obtained a 1.5 m sediment core that completely consists of brown fibrous *mallín* (Fig. 2c). No tephras were found in this core. As in the previous cores, rather minor fluctuations in mineral magnetic inputs were found in this core, with minor increases in the present, ca. 155 BP, 285 BP, and right before 3190 BP (Fig. 2c).

3.2 Charcoal analyses

Charcoal accumulation rates (CHAR pieces cm^{-2} yr^{-1}) at *mallín* Tortel show charcoal fluctuation through the first three millennia, with CHAR reaching prominent maxima in the 1970s AD and ca. 300 cal yr BP, 550 cal yr BP, 875–1375 cal yr BP, 2100 cal yr BP, 2375 cal yr BP, and 2975 cal yr BP. A macroscopic charcoal peak is significant (from the background charcoal noise) only in the 1970s AD (Fig. 4a). From *mallín* Leal we obtained a charcoal record spanning the last four millennia with CHAR peaks in the 1950s AD, ca. 200 cal yr BP, 450 cal yr BP, 675 cal yr BP, 1150 cal yr BP, 1525 cal yr BP, 3375 cal yr BP, and 3750 cal yr BP (Fig. 4b). Most of these peaks were detected from the background noise, but did not reach significance ($P > 0.05$), except for the 1950s AD CHAR peak. In contrast to the previous two *mallines*, from the *mallín* Casanova we obtained a ca. 10ka long charcoal record, with multiple detected (but not significant) CHAR peaks. Four significantly high CHAR peaks were found in 1920s AD, ca. 700 cal yr BP, 8050 cal yr BP, 9850 cal yr BP, and 10 200 cal yr BP (Fig. 4c). The

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CHAR records of the *mallines* located at the opposite ends of the Baker watershed (i.e., *mallines* Tortel and Casanova) show a strong temporal synchrony ($r_P = 0.83$, $P < 0.05$), whereas *mallín* Leal was not strongly correlated with either of the CHAR records from the Baker watershed. The low variability in background charcoal amounts at *mallines* Leal and Tortel (Fig. 4) precluded the computation of correlations.

3.3 Detection and calibration of the charcoal records using fire-scar records

CHAR peaks tend to coincide with high fire activity recorded by tree-ring fire scars, but not all periods of frequent fire scars were recorded by the charcoal records (Fig. 5). There is a clear correspondence between both proxies in the 1950s–1970s AD in all records (Fig. 5a, b); the high density of years with high percentages of sites recording fire scars corresponds with peaks in CHAR in the 1950s–1970s AD. In the Baker watershed, there is overlap in the 1920s and the 1850s between the *mallín* Casanova CHAR and the fire scar record (Fig. 5a). Despite the reduced sample depths in the aggregated fire scar record in the Baker watershed, there is some correspondence between the CHARs from both *mallines* and the fire scar records around the 1600s–1620s AD (Fig. 5a). At *mallín* Leal there is relatively strong correspondence of the CHAR record with the fire scar records in the 1920s and 1700s–1720s AD from both the Bravo and Quetru-Pascua watersheds (Fig. 5b). In both the CHAR and fire-scar records from all three watersheds, fire activity appears to decline in the 1920s and increase again in the 1940s (Fig. 5).

There is large variation in the correspondence between the CHARs and the fire scar records at each site as shown by the correlation coefficients. At the Baker watershed the same-site paired CHARs and fire scar records (during all fire years; circles) are highly correlated ($P < 0.05$), but the opposite is true at the *mallín* Leal (circles in Fig. 6a–c). As expected these correlations tended to decline over distance from the sedimentary sample site, yet at all three *mallines* the correlations were significant even for the fire scar site most distant from the cored bog. At *mallín* Casanova, a high temporal correspondence ($P < 0.05$) was found between the background charcoal and all fire years record across the entire watershed (black squares in Fig. 6b). For *mallín* Casanova, high correlations also were found between the background charcoal and the record of widespread fire years within 10 kilometres from the coring site (inverted triangles in Fig. 5b).

4 Discussion

4.1 Fire history interpretations from sedimentary charcoal records

4.1.1 Transport and taphonomic processes uncertainties

There is a high uncertainty regarding the production and deposition processes of sedimentary records from bogs and wetlands (Whitlock and Anderson, 2003). When sedimentary charcoal records are obtained from lakes, charcoal particles from terrestrial fires are generally assumed to have landed on lakes after being transported by wind or surface runoff. Topography influences post-fire runoff depending among other factors on slope angle of the burned hills and distance to the lake. In this study all sampled *mallines* are surrounded by rugged mountains with steep slopes that adjoin the sedimentary basin. However, the amount of charcoal that is produced in the catchment and then is subsequently deposited in the *mallín* sediments is unknown. Previous studies of paired charcoal and fire scar records set on bogs have suggested that high percent of charcoal might not reach the deep sediments of bog interiors. This might be due to the fact that charcoal particles are filtered out by vegetation growing on the bogs and re-deposition is less common (Allen et al., 2008). Despite these difficulties and uncertainties, high charcoal concentrations were found throughout the Holocene in the *mallines* sampled in the current study. This is especially clear in all watersheds since the arrival and permanent establishment of Euro-Chilean settlers, where charcoal peaks and fire scar evidence closely co-occur. Other uncertainties related to bioturbation due to native or introduced mammals could be discarded in the study area. Native

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mammals are rare and generally prefer ridge habitats, and the introduction of cattle took place very recently (in the last ca. 70 yr; Holz and Veblen, 2011b) and should not have largely altered the stratigraphy of the sampled *mallines*.

4.1.2 Detection and calibration of the charcoal records using fire-scar records

Records of high fire activity derived from CHAR generally coincided with periods during which the fire-scar record also indicated at least some and usually abundant fire years. However, at annual and decadal time scales there were numerous instances in which the fire-scar record indicated moderate to high levels of fire activity that were not detected by the CHAR analyses. We speculate that some of the discrepancy between the two records may be a greater sensitivity of the fire-scar record to low-severity fire events that can be surveyed by fire-scar recording trees whereas low-severity fires may not be recorded in the sedimentary record. High-severity (stand-replacing) fire events are more likely to be recorded in the CHAR record. Similar interpretations of the differential sensitivity of the two types of fire proxies to fires of different severities have been suggested for fire history records in the western US (Whitlock et al., 2004; Allen et al., 2008). In contrast, in a study conducted in boreal forests in Finland, fire activity recorded by both proxies corresponded well in a regime with low-severity and high fire frequency (Pitkänen et al., 1999).

The spatial correspondence among the charcoal and fire scar records and their variation in the studied watersheds indicate that these records might be affected by several factors. Among others, these include: the geographical alignment of the studied watershed in relation to the prevailing SWW, the rugged topography of the area, the strong precipitation gradient and the effect of moderate to severe drought on fire activity, human presence, the fuel type burned in previous fires and the criterion for selecting charcoal particle size. For instance, the predominant wind direction (west-east) could explain both the high correspondence between both CHAR records within the Baker watershed, and the low correspondence of these CHARs with the *mallín* Leal record. Similarly, in the Baker watershed both the CHARs from and fire-scar records at both

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mallines located at its opposite end are highly synchronous. Some variations however, could be explained by relative intensity of human activity as people may have preferred to occupy the more navigable Baker watershed, than the narrower canyons of the Bravo and Quetru-Pascua watersheds. In addition, at *mallín* Leal there was no correspondence between the local CHAR and its paired fire scar record. This could be explained by the abundant, in-situ, fine fuels that characterized the study area and that could mostly create peaks of micro-particles (<125 µm). Previous studies in similar ecosystems in the boreal forests in Finland found that microcharcoal from both sediment cores and experimental burning were associated in some cases to local, rather than extra-local fire events (Pitkänen et al., 1999). Therefore, the use of the 99th percentile for the CHAR development might not be best suited for fine-fuel dominated *mallines*. In some areas, local events might be surface fire only, without the creation of large enough particles, and/or enough heat for currents of lifting air to travel extensively.

4.2 Fire reconstruction and climate

The charcoal records reported here extend by several thousand years back in time the existing fire history record for our study area in western Patagonia (47–48° S), where previously only fire scar records existed for the ca. 1550–2005 period (Holz and Veblen, 2011b). Previous studies focused on fire activity both using fire-scar or charcoal emphasize the influence that climate and human activity have on fire regimes in the region (Holz and Veblen, 2011b; Veblen et al., 1999, 2011; Huber et al., 2004; Whitlock et al., 2007).

The role of regional-scale climate variability is highlighted by the general correspondence between our charcoal records and previous charcoal-based *fire* studies across SSA. For instance, high fire activity have been dated ca. 1.2–1.8 age cal ka BP at 52° S (Moreno et al., 2009), which partially corresponds with charcoal peaks in all three *mallines* in our study area. Furthermore, charcoal peaks dated in ca. 7–11 age cal ka BP at the *mallín* Casanova have also been reported in northern Patagonia (42° S, Moreno et al., 2001, 43° S, Whitlock et al., 2006; Abarzua and Moreno, 2008;

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44° S; Haberle and Bennett, 2004), southern Patagonia (ca. 52° S, Huber and Markgraf, 2003; Huber et al., 2004), through Tierra del Fuego (ca. 55° S, Heusser, 1995). Furthermore, increase in charcoal at all *mallines* at ca. 550–650 and 1600–1800 age cal BP (Fig. 5, 7a–c) occurs concomitantly with reconstructed dry periods recorded at 41° S (Fig. 7f) Lamy et al., 2001), 44° S (Fig. 7g; Sepúlveda et al., 2009), and 53° S (Fig. 7h; Lamy et al., 2010). Changes in precipitation throughout the Holocene in SSA have been attributed to both ENSO events (Sepúlveda et al., 2009) and latitudinal shifts of the SWW (Varma et al., 2011). Overall, these relationships are currently valid as confirmed by studies using instrumental climate data (Montecinos and Aceituno, 2003; Garreaud, 2007; Garreaud et al., 2009). Additionally, the Southern Annular Mode and the decadal-scale ENSO-like Oscillation (i.e., expressed as PDO and IPO) are strongly teleconnected to precipitation patterns in SSA (Garreaud et al., 2009).

Some of the synchronous charcoal peaks (e.g. 700, 1300 and 1600 BP) also coincide with higher than average frequency of warm ENSO events (Moy et al., 2002; Koutavas and Sachs, 2008) that coincided with both higher precipitation at 41–44° S and lower precipitation at 53° S (Fig. 7f–h). This is consistent with recent studies that have proposed an analogy between the SSW dynamics throughout the Holocene and the modern SWW seasonal fluctuation. During the summer season the SWW's belt contracts and the intensity within its core (at ca. 53° S) strengthens, and during the winter the belt expands northward (34° S) and wind intensity in the core (53° S) decreases (Lamy et al., 2010). These seasonal patterns are primarily observed during the early and late Holocene, respectively (Lamy et al., 2010), and it is the winter pattern that fits with the precipitation patterns and charcoal peaks described above. However, charcoal increased prior to the onset of more frequent ENSO events in the late Holocene (i.e., ca. 8 and 10 kyr BP), which suggests that fire activity in our study area was governed by factors other than ENSO alone (Fig. 7a–c, d).

Previous climate-fire studies located at these same sites that were based on tree-ring fire records and used tree-ring based climate reconstructions showed that for the last ca. 250 yr, drought-events primarily resulted from the positive phase of SAM (Holz and Veblen, 2011, 2011a). The positive phase of SAM is associated with decreased surface pressure over Antarctica and a strengthening and poleward shift of the SWW (Garreaud et al., 2009), which results in lower precipitation in Patagonia (i.e., south of ca. 37° S; Aravena and Luckman, 2009). A strengthening and poleward shift of the SWW could have resulted in the increased precipitation at 53° S in the early-to-mid Holocene (i.e. ca. 8 and 10 kyr BP), which in turn fits with high charcoal peaks at our study area, and has been previously suggested (Moreno, 2004). Previous fire-climate studies have also indicated that when SAM was in its positive phase, fires were more frequent concomitantly with Pacific-wide warmer conditions at decadal-scales (i.e. positive PDO; Holz and Veblen, 2011a). PDO is positively correlated with annual drought in southern Chile, (Garreaud et al., 2009). Previous SST reconstructions also suggest that not all warming events of the coast of Chile at 41° S (Fig. 7e; Lamy et al., 2007) were directly caused by tropical Pacific ENSO (Fig. 7d; Moy et al., 2002) and/or the Cold Tongue Index (Fig. 7d; Koutavas and Sachs, 2008) records. Overall, this evidence suggests that large-scale climate modes with origins from both low- and high-latitudes (alone and in combination) have been teleconnected with drought events and fire activity in SSA.

4.3 Fire reconstruction and people

Interpretations of the relative roles played by humans versus lightning in accounting for long-term variations in wildfire activity have varied substantially. Whereas some authors have stressed the importance of prehistoric human activities (Heusser, 1987, 1994; Haberle and Bennett, 2004), others instead have highlighted the importance of climatic control and assumed that during the Holocene lightning ignitions were sufficiently frequent to not be a limiting factor (Markgraf and Anderson, 1994; Moreno et al., 2001).

Indigenous people are known to have inhabited the study area at the time of European arrival (Ivanoff 2004). Archaeological (Goñi et al., 2004) and ethnohistorical (Martinic, 1977, 2005) evidence from southern Chile indicates that Indigenous people managed their landscape with fire. Furthermore, fire-scar based research in our study area indicates that prior to European arrival Indigenous people burnt more frequently than previously assumed Holz and Veblen, 2011b). Our results provide new evidence of high correspondence between the CHAR records of the *mallines* located at the opposite ends of the Baker watershed (i.e., *mallines* Tortel and Casanova), but low correspondence with the *mallín* Leal record. Potentially, differences in local climatic conditions could account for the lack of correspondence but the two watersheds are at overlapping longitudes and separated by only ca. 28 km. It is more likely, that under a common regional climate such disparity in fire activity suggests human presence in the Baker but not in the area of *mallín* Leal (at least for the last ca. 3–4 age cal ka BP). Although published data are lacking, the consensus among archeologists working in the region is that no prehistoric peoples inhabited our study areas before ca. 1000 BP (Francisco Mena; personal communication, 4 August 2011).

There is no currently available archaeological evidence that support any human presence in our study area during the charcoal peaks of ca. 7–11 age cal ka BP (Francisco Mena, personal communication, 4 August 2011). Other than the influence of the Hudson eruption documented here (Fig. 2), these charcoal peaks suggest that climatic conditions were different than modern ones, and that lightning-set fires might have been more common that today. Although currently uncommon, lightning-induced fire scars were observed in our study area (Holz and Veblen, 2009), and lightning-set fires have more than tripled in northern Patagonia since the climate shift in the late 1970s (Veblen et al., 2008). This suggests that relative role of lightning as an ignition source probably also varied greatly over the Holocene, and that lightning observations during the 20th century may not provide completely suitable analogues for interpreting prehistoric records. Lack of lightning may account for the lack of charcoal peaks during the period from ca. 4700 to 5000 BP when climate conditions were conducive to fire activity (i.e., dry periods at 41–44° S and at 53° S and warm ENSO peaks; Fig. 7d, f–h). In contrast, it appears that in the early Holocene climate conditions were conducive for convective storms and lightning was the source of ignition for the charcoal peaks recorded at *mallín* Casanova. In the mid-Holocene, climate conditions appear not to have been suitable for lightning set fires. With the arrival of Indigenous groups to the area in the late Holocene, fire activity was amplified by these groups during drought events. Since the arrival and permanent establishment of Euro-Chilean settlers, fire activity increased considerably and is clearly outside of the historical range of variability over most of the Holocene (Fig. 5; Holz and Veblen, 2011b).

5 Conclusions

Our study contributes relevant information to fire history in the western Patagonia rainforest region of SSA by examining temporal and spatial correspondence among charcoal and fire scar records in three watersheds. Our results show that CHAR records tend to coincide with the fire scar records during some periods, but in general they did not detect all periods of fire activity recorded by the tree-ring fire history record. Potentially, low severity fire events that burned mainly herbaceous and other fine fuels in *mallines* are not recorded in the sedimentary records of these bogs. This suggests that potentially the procedure used for developing peaks in CHAR might not be best suited for fine-fuel dominated *mallines*. Despite these and other uncertainties about the production and deposition processes of sedimentary records from *mallines*, significant CHAR peaks were found throughout the Holocene.

Some of the peaks in CHAR records found in all three *mallines* are synchronous and tend to coincide with fire records from northern and southern SSA over a latitudinal span from ca. 42 to 55° S, which indicates large-scale climate control on fire activity. Whereas the onset of more frequent ENSO events seems to be reflected by increased wildfire activity in the late Holocene, changes in the latitudinal position or intensity of the SWW appear to account for charcoal peaks in the early Holocene. Overall, it seems that fire activity throughout the Holocene in western Patagonia has responded to regional climate variation affecting a broad region of SSA that is teleconnected to both tropical- and high-latitude climate drivers – ENSO and SAM. Although sources of ignition during the pre-historic period cannot be directly measured, the available

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archaeological knowledge of our study area strongly implies that the early Holocene peak in fire activity was not dependent on human presence. Finally, the increased fire activity during the 20th century that was concomitantly recorded by charcoal from all *mallines* and all fire scar sites is outside the range of variability characteristic of these ecosystems over many centuries and probably millennia.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/7/3203/2011/cpd-7-3203-2011-supplement.pdf.

Acknowledgements. Research was supported by the National Geographic Society (grant 7988-06), the National Science Foundation (awards 0602166 and 0956552), and the Beverly Sears Small Grants Program, and the Council on Research and Creative Research of the Graduate School at CU Boulder. For sharing with us his profound knowledge and observations on the archaeology of our study area, we thank Francisco Mena of the Centro de Investigación en Ecosistemas de la Patagonia (CIEP) in Coyhaique, Chile.

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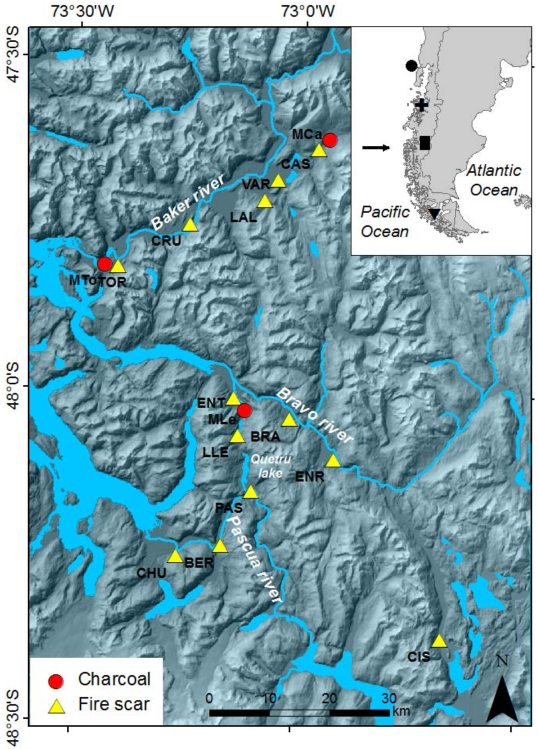

Fig. 1. Map of Patagonia showing coring and fire scar sites in the Baker, Bravo and Quetru-Pascua watersheds. In the inset map of southern South America (SSA), black rectangle, arrows, black and white circles, and black triangle represent the study area, the southerly westerly winds (SWW) predominant direction, precipitation reconstructions (and hence, the position of the SWW) at 41° S (Lamy et al., 2001), 44° S (Sepúlveda et al., 2009), and 53° S (Lamy et al., 2010), respectively. Site characteristics are outlined in Tables S1 and S2 in the Supplement.

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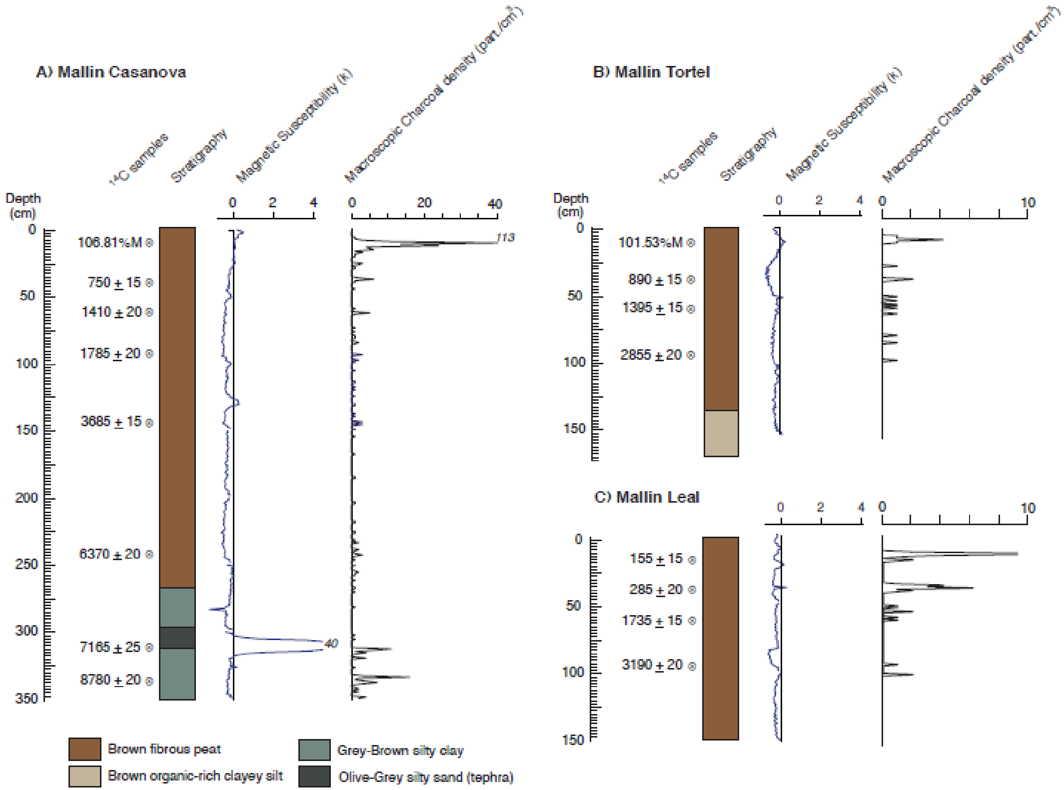

Fig. 2. Radiocarbon dates, stratigraphy, magnetic susceptibility, and macroscopic charcoal of each of the three sampled *mallines* **(a)** Casanova, **(b)** Tortel, and **(c)** Leal.

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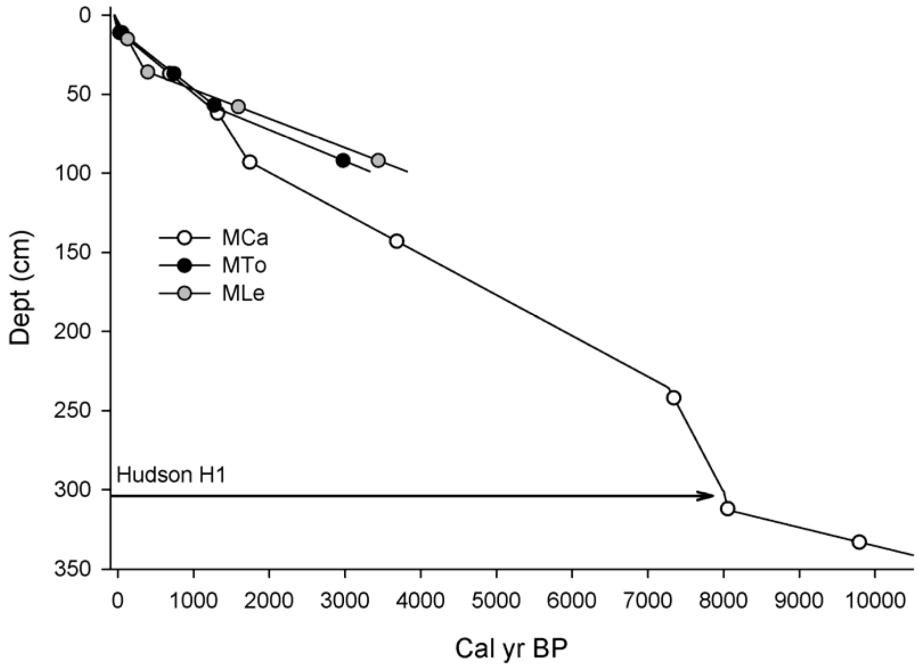

Fig. 3. Linear age-depth model for the composite charcoal records of the calibrated radiocarbon dates. ^{14}C dating errors range is ±15–25 yr and is imperceptible at this age-scale resolution. The arrow indicates the position of the Hudson Vn. H1 tephra found in the *mallín* Casanova (MCa; see also Fig. 2a). MTo and MLe stand for *mallines* Tortel and Leal.

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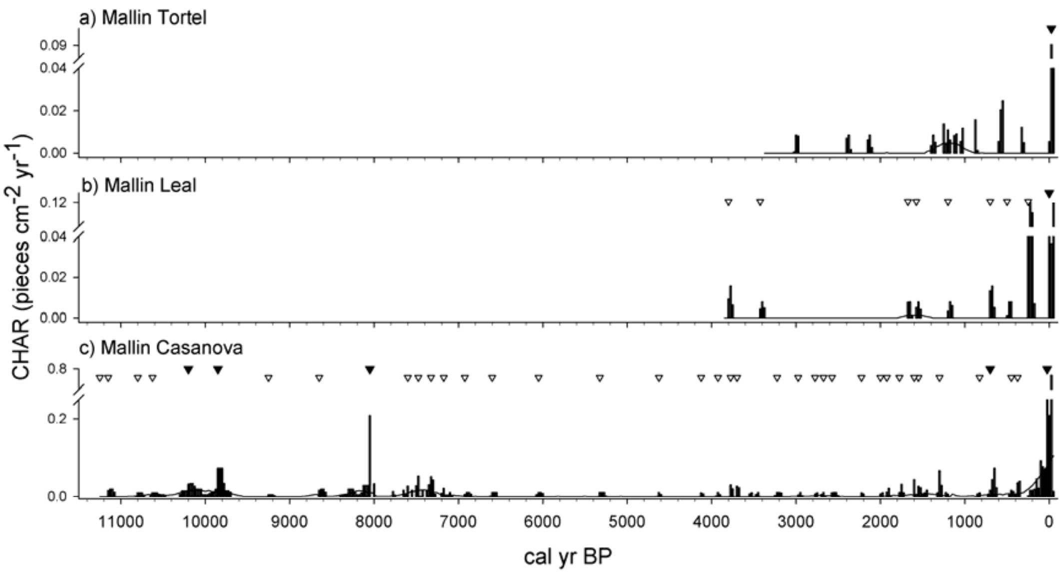

Fig. 4. Charcoal peak analysis using CharAnalysis (Higuera et al., 2009). Charcoal accumulation rates (CHAR pieces $cm^{-2}\,yr^{-1}$) are plotted on an age axis and interpolated to 25 yr intervals. Background charcoal (black line) defined by 1000-yr trends. In order to separate charcoal peaks from the background noise, we used a Gaussian mixture model to estimate the mean and variance of the noise distribution. Fire events were identified as peaks exceeding the 99th percentile of the noise distribution. ($P > 0.05$, white inverted triangles; $P < 0.001$, solid black inverted triangles).

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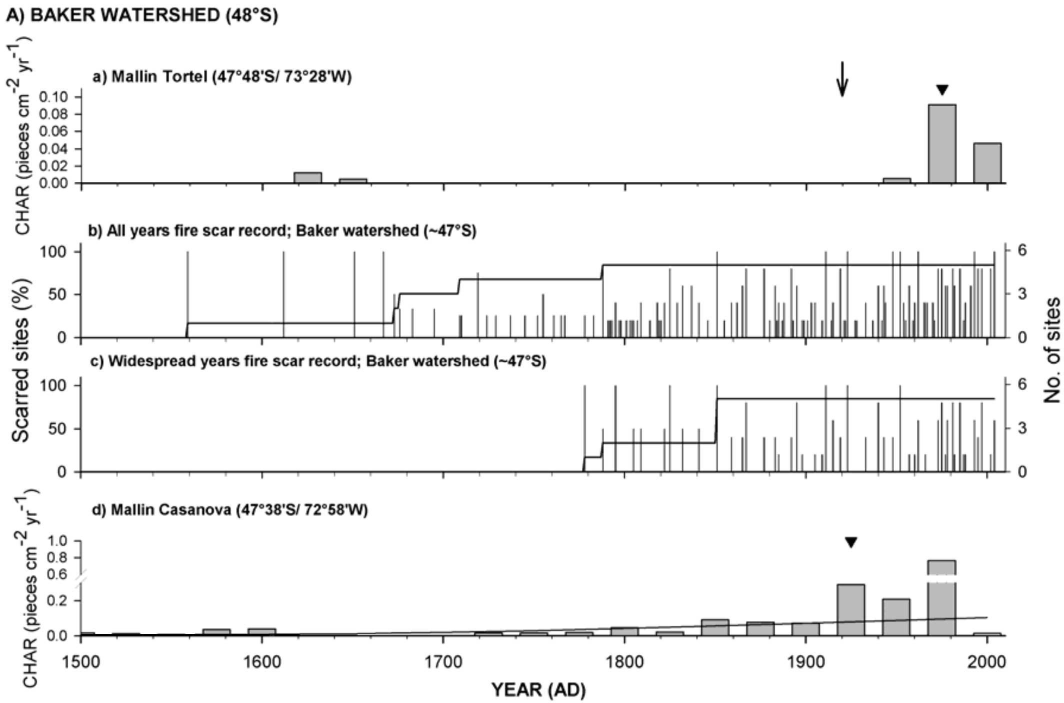

Fig. 5a. Caption on next page.

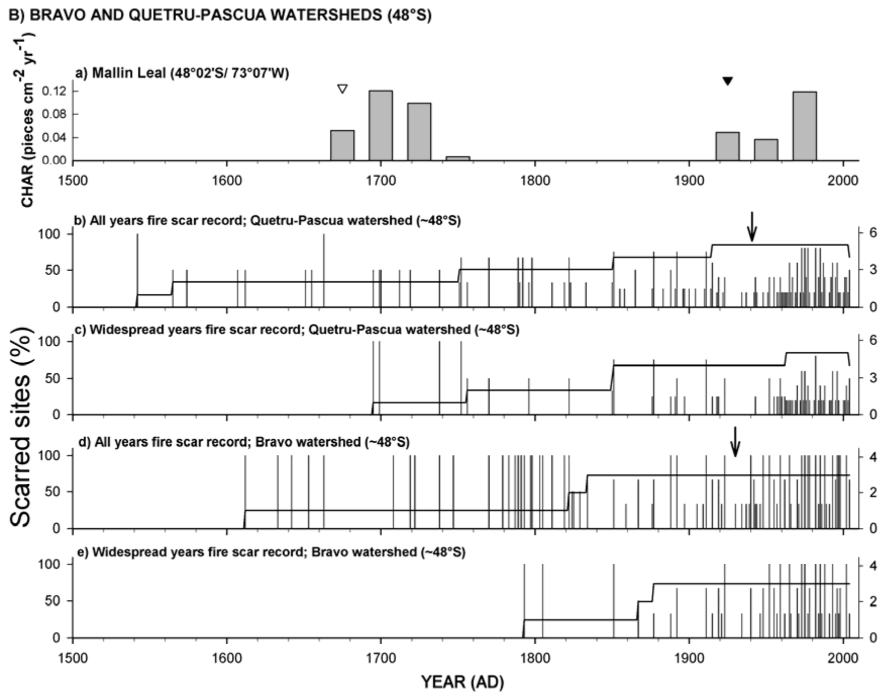

Fig. 5b. Paired fire history based on fire scar and CHAR peaks in **(a)** the Baker watershed and **(b)** the Bravo and Quetru-Pascua watersheds. Fire scar indices for all fire and widespread fire years are presented by watershed. All fire years in the composite of each sample area are defined as (minimum ≥1 scarred tree per site). Widespread fire years in the composite of each sample area are defined as (minimum of ≥20 % of trees scarred in each watershed including individual sites that had a minimum of 2 scarred trees). The horizontal line in each fire scar composite represents the number of sites available for scarring in each watershed. The vertical arrow at each panel represents the Euro-Chilean period in each watershed as defined by (Holz and Veblen (2011b). Note that number of sites samples varies among watersheds. CHAR values and symbols are defined in Fig. 4.

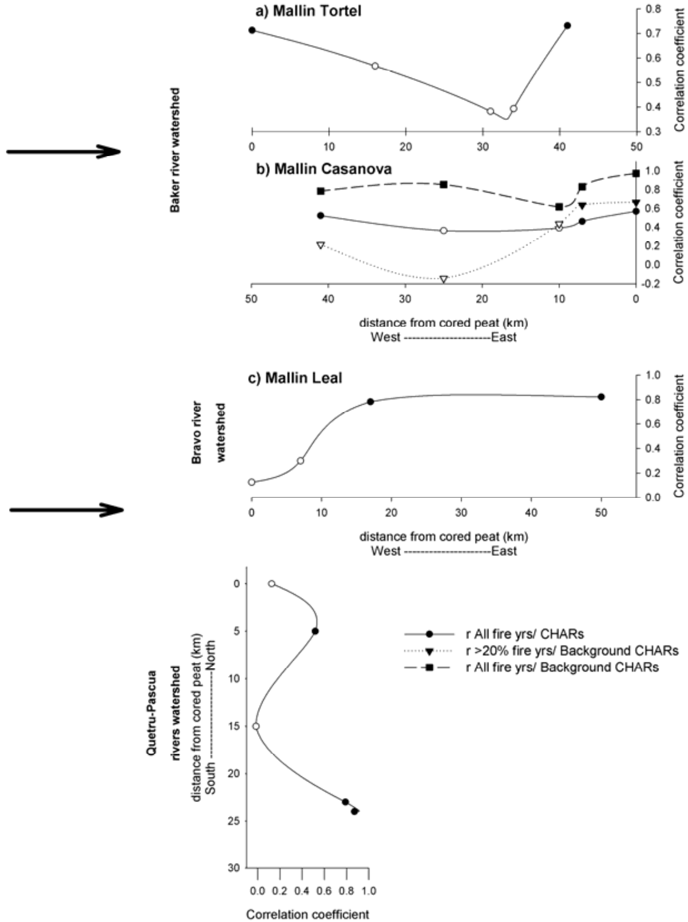

Fig. 6. Caption on next page.

Fig. 6. Spatial variation of correlation coefficients between individual fire scar records (smoothed) and the **(a)** *mallín* Tortel, **(b)** *mallín* Casanova, and **(c)** *mallín* Leal charcoal records. Correlations between records of smoothed all fire years and CHARs (circles), smoothed all fire years and Background CHARs (squares), and smoothed widespread fire years and Background CHARs (inverted triangles) are reported. Background CHARs were found only in the *mallín* Casanova. Significant Spearman correlations ($P < 0.05$) between records are shown in solid symbols (i.e. black circles, inversed triangles, and black squares). The horizontal and vertical displays of the panels represent the west-east and north-south gradients from each coring site, respectively. The black horizontal arrow represents the direction of the prevailing southern westerly winds (SWW) in relation to the sampled sites. The periods used for the smoothing of the fire scar records are in Talbe S1 in the Supplement.

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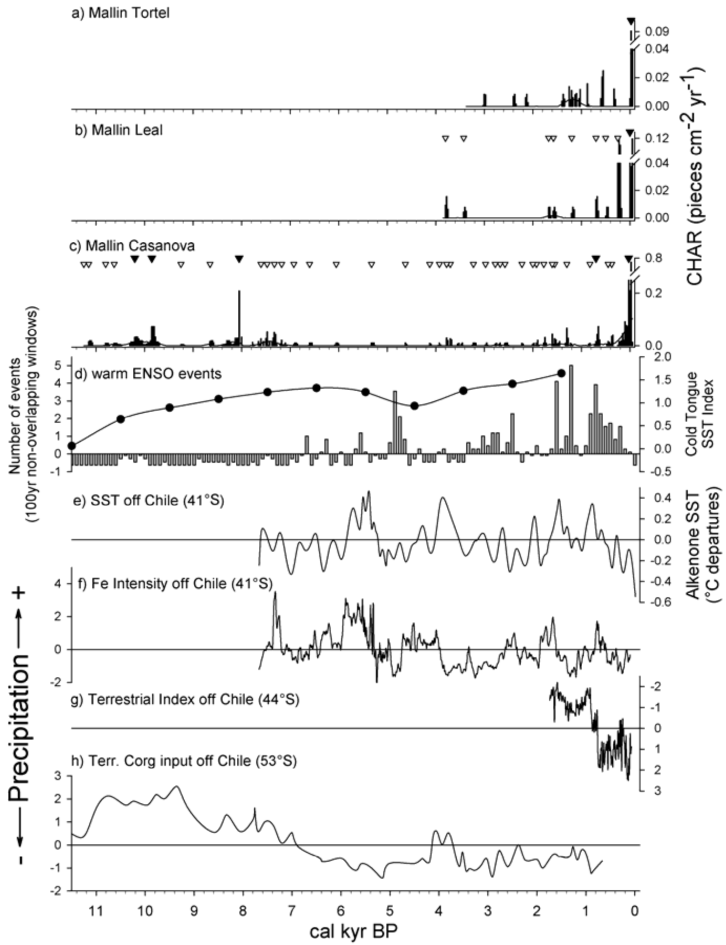

Fig. 7. Caption on next page.

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Fig. 7. CHAR peaks **(a–c)** and climate proxy. CHAR peaks as in Fig. 3, and climate reconstructions are for: **(d)** ENSO (bars; Moy et al., 2002) and Cold Tongue SST Index (Koutavas and Sachs, 2008), **(e)** Alkenone (SST at 41° S; Lamy et al., 2007), **(f)** Fe intensity (precipitation and linked position of the southern westerly winds, SWW; based on the GeoB3313-1 iron record at 41° S ; Lamy et al., 2001), **(g)** Terrestrial Index (PC1 for the C/N ratio, δ^{13}C, and δ^{15}N at 44° S; Sepúlveda et al., 2009), and **(h)** terrestrial organic carbon accumulation (precipitation and linked position of the southern westerly winds, SWW; based on core TML1 at 53° S ; Lamy et al., 2010). Antiphase trends between **(f)** the Cold Tongue SST Index and **(h)** the terrestrial organic carbon represents strength of SSW in SSA (Lamy et al., 2010).