Hum Ecol (2017) 45:205–219
DOI 10.1007/s10745-016-9879-9

Divergent Fire Regimes in Two Contrasting Mediterranean Chestnut Forest Landscapes

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Published online: 23 December 2016

Abstract Humans have historically played a critical role in the management of Mediterranean-type ecosystems (MTEs) through traditional fire use. Although chestnut forests are widespread across the Mediterranean Basin, little is known about their historical fire regimes. Our goal here is to generate testable hypotheses about the drivers of fire regime dynamics in chestnut dominated ecosystems. To examine anthropogenic fire management we selected two sites in Spain that have similar biophysical characteristics but divergent levels of economic development and fire management policies. Fire regime-landscape feedbacks were characterized through a pilot dendroecological study, official fire statistics, aerial photography and forest inventory data. Our results suggest that fire incidence in both sites has increased since the pre-industrial era but fire season, fire size, and forest structure have changed to a greater extent in the more developed site. These changes are probably driven by the decline in annual anthropogenic burning of litterfall by local communities at the more developed site during the non-vegetative season.

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Keywords Mediterranean fire ecology · Spain · Chestnut forest ecosystems (*Castanea sativa* mill.) · Traditional ecological knowledge · Traditional fire knowledge · Coupled human and natural systems theory · Dendroecology

Introduction

"Fire is the thunderbolt that steers all things."
Heraclitus (ca 540-ca 480 B.C.)

Anthropogenic fires have played a key role in shaping the structures and processes of Mediterranean-type ecosystems (MTEs) in long-inhabited areas of the world such as the Mediterranean Basin (Grove and Rackham 2000; Pausas 2004). In the Iberian Peninsula, MTEs dominated by chestnut (*Castanea sativa* Mill.) in particular have been actively managed by humans for centuries (Conedera *et al.* 2004). The sweet chestnut (*Castanea sativa* Mill.) is a deciduous hardwood tree species belonging to the Fagaceae family, which seems to be native to the Iberian Peninsula with glacial refugia having been identified in Spain and Portugal (Postigo-Mijarra *et al.* 2010). Chestnuts have been widely cultivated throughout the temperate world, particularly across the Mediterranean Basin (Fig. 1) and their geographical range is closely associated with the activities of pre-industrial era societies (Conedera *et al.* 2004). Currently, sweet chestnut forests are mainly concentrated in southern Europe (France, Italy, Spain, Portugal and Switzerland) where there is a long tradition of their cultivation as groves for nuts and timber production (Conedera *et al.* 2004).

Consistent with other authors, we therefore assume that humans should be considered an integral part of chestnut ecosystems due to, among other things, the role played by anthropogenic burning in influencing historical fire regimes (e.g.,

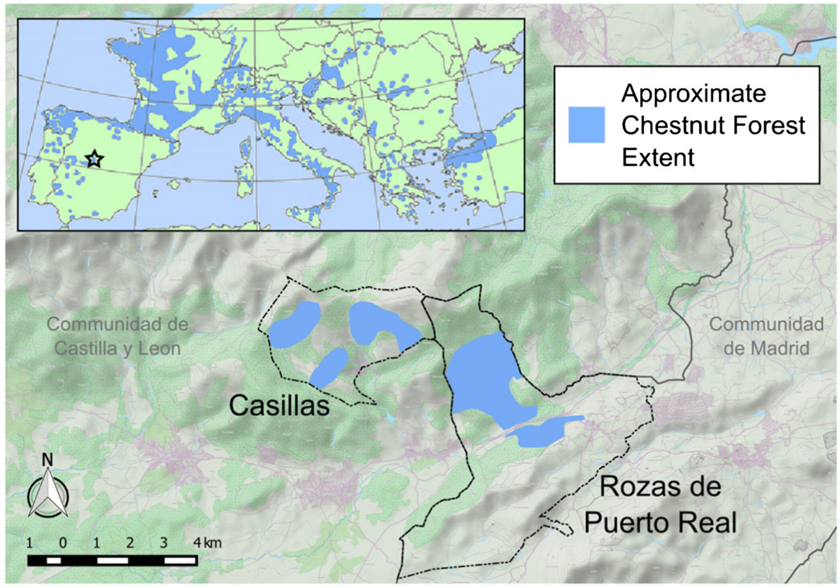


Fig. 1 Distribution area of sweet chestnut (*Castanea sativa*) forests throughout Europe. The star indicates the location of the Casillas and Rozas study sites in central Spain (the map was modified from http://www.euforgen.org/distribution-maps/) and approximate chestnut forest extent within them.

Keane *et al.* 2009). However, socioeconomic induced changes, such as the abandonment of traditional ecosystem management practices and uses, along with climate change and other factors, mean that modifications of MTE fire regimes can lead to an increased probability of large fire occurrence (Fernandes *et al.* 2013). To provide insights into the little-researched fire ecology of chestnut MTEs – and the possible implications of contemporary fire management changes in them – we explore the histories and divergent dynamics of anthropogenic fire regimes in two divergently developed chestnut-dominated landscapes in central Spain.

Managers and scholars are increasingly concerned about the resilience of existing chestnut landscapes to new emerging disturbance regimes, particularly in light of widespread rural abandonment and the demise of traditional pre-industrial era management practices (Grund *et al.* 2005; Krebs *et al.* 2012; Pezzatti *et al.* 2013; San Roman *et al.* 2013; Zlatanov *et al.* 2013). Previous efforts to identify historical fire regime "change points" in chestnut forest ecosystems have focused on the analysis of fire frequency and spread or burnt area, concluding that only strict anthropogenic fire bans can lead to the adequate management of both changing attributes (e.g., Pezzatti *et al.* 2013). We suggest that a combination of human and biophysical system factors – forest structure fuel changes, transformed ignition patterns (particularly in seasonality) and climate change – that in the literature are often referred to as the "megafire triangle," may also be playing an important role in driving these fire regime changes (Fig. 2; Stephens *et al.* 2014). In light of this and to mitigate the risk of "larger fires" (officially defined in Spain as >500 ha), landscape managers now seem to face a choice between increased fire suppression and preventive prescribed burning (Fernandes *et al.* 2013; Khabarov *et al.* 2016).

We selected two study areas located in similar biophysical environments – and thus assumed ecological factors to be as constant as possible in a non-laboratory setting – but with divergent human system drivers. The main difference lies in their uneven levels of economic development and the "looseness" of feedbacks resulting from the dissimilar fire management strategies of their public administrations (Hull *et al.* 2015). The importance of different types of feedback between human activity and environmental processes has been underlined by the recent development of conceptual frameworks such as Coupled Human and Natural Systems (CHANS) (Alberti *et al.* 2011; Hull *et al.* 2015). In the CHANS

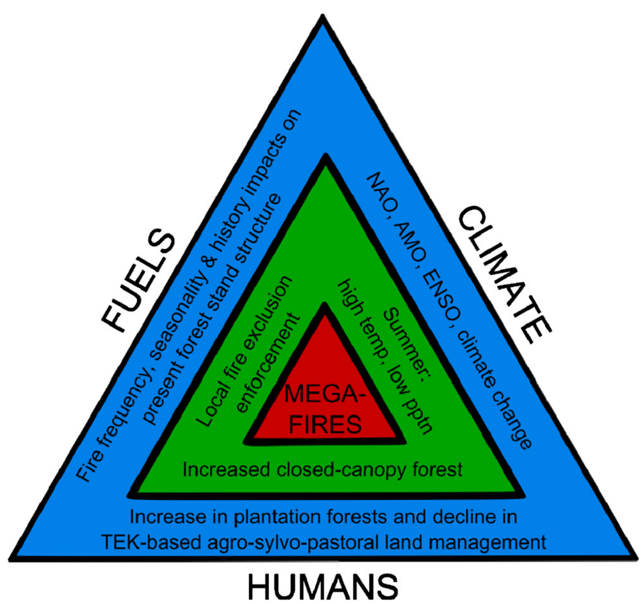


Fig. 2 The "megafire triangle" and its transposition to the local conditions present in the two unevenly developed chestnut forest CHANS sites (figure adapted from Stephens *et al.* 2014)

framework, “loose feedbacks” refer to “legacy effects” and, specifically in this case, to traditional pre-industrial era landscape management practices that may influence vegetation succession patterns over decades or centuries (Perry and Millington 2008).

Here, we examine the role of Traditional Ecological Knowledge (TEK; Berkes *et al.* 2000), and its derivative Traditional Fire Knowledge-based management practices (TFK; Seijo *et al.* 2015), in conditioning these feedbacks. TFK can be defined as “fire-related knowledge, beliefs, and practices that have been developed and applied on specific landscapes for specific purposes by long time inhabitants” (Huffman 2013:1) and is a variant of TEK. In turn, TEK is “the cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down in generations by cultural transmission, about relationships of living beings [including humans] with one another and with their environment” (Berkes *et al.* 2000:1). This work opens up a discussion of whether current fire-regime dynamics are within the historical range of variability (HRV) for chestnut forest MTEs in our study sites. We discuss how the hypotheses we generate based on this initial case study evidence, if corroborated by further research, may be relevant to the management of chestnut landscapes throughout the Mediterranean basin, particularly with respect to TEK and TFK.

Materials and Methods

To address these issues we reconstructed historical fire regimes by using complementary tools such as official statistics on fire incidence in both municipalities and a pilot dendroecology study (Fulé *et al.* 2008; Christopoulou *et al.* 2013). To characterize feedbacks with forest structure and composition we analyzed forest inventory data and historical aerial photographic records. In particular, we analyzed the divergent dynamics of fire regimes throughout the twentieth century in our two study landscapes, focusing on the decades immediately preceding and following the industrialization process initiated by the Spanish state in the forestry sector in the 1960s (Seijo 2005; Seijo and Gray 2012). To do so we deployed an interdisciplinary approach combining a dendroecological-based pilot study of old growth chestnut tree groves and analyses of historical forest structure based on aerial photography records and forest inventory data.

Study Species and Site Selection

The chestnut forest landscapes of our study area are located in the foothills of the mountains of Gredos (central Spain). Palynological studies have verified the presence of the species in the area since 500 BC (López-Sáez *et al.* 2009). Research was conducted in the municipalities of Casillas, autonomous community of Castilla y León, and Rozas de Puerto Real, autonomous community of Madrid, in central Spain (Fig. 1). Through this careful landscape selection we considered that the biophysical variables driving fire regime changes could be held constant, as far as possible in a non-laboratory setting, so as to better highlight the connections between ecological feedbacks in both sites with contrasting fire management and socioeconomic drivers. This methodological approach has yielded interesting findings on the dynamics of changing fire regimes in other MTEs (e.g., Minnich 1983).

Study sites were selected so as to represent different anthropogenic fire regimes in MTEs. Seijo and Gray (2012) hypothesize that uneven processes of state-led political and economic development have driven, to varying degrees, the fire regime changes taking place at present in many MTEs. These changes seem to be mediated by the differing degrees of implementation of accompanying state fire exclusion policies and the divergent impact of state-led economic development policies in the forestry sector on the economic development of pre-industrial local community economies (Seijo and Gray 2012). We selected Casillas and Rozas as study sites because they are separated by an intra-state political boundary between Spanish autonomous communities (i.e., regional governments) and are therefore subject to different administrative fire management policies.

The two municipalities also exhibit markedly different levels of economic development as suggested by various basic economic indicators. There are significant differences between the two municipalities in both per capita income levels (GDP per capita Casillas €16,290 vs. Rozas €23,929; AIS 2014) and occupational structure (population employed in the service sector is 77.3% in Rozas compared to 28.6% in Casillas). These indicators suggest that Rozas may have already made the transition into a post-industrial, service-sector based economy (Touraine 1971) while Casillas remains in the industrializing phase as evidenced by the larger proportion of its population employed in the primary (6.2% vs Rozas’ 2.1%) and secondary (65.2% vs. Rozas’ 19.6%) sectors (Caja España 2011). Furthermore, costs of fire exclusion per hectare between the autonomous community governments of Castilla y Leon (Casillas) and Madrid (Rozas) differ significantly – €14 per hectare and €75 per hectare respectively (ASEMFO 2006). We use these human system data as proxy indicators for the contrasting human system factors that may be driving to different degrees fire regime changes since industrialization in both sites (see below).

However, while differing significantly in economic development and investments in fire exclusion policy implementation, the municipalities share similarities in their biophysical conditions. Being geographically adjacent, both sites are characterized by dry-summer Mediterranean climate, with precipitation concentrated in the autumn, spring and winter months. Mean annual temperature for Rozas is 12.1 °C and 13.4 °C for Casillas, based on data from meteorological stations located in each village (Rozas, 40° 29′ 31″ N, 3° 52′ 28″ W, 712 m a.s.l., period of data 1983–2013; Casillas, 40° 19′23″ N, 4° 34′ 20″ W, 1012 m a.s.l., period of data 1995–2013). Mean annual precipitation is 831 mm in Rozas and 978 mm in Casillas. To study historical trends in annual mean temperature and total precipitation we obtained data from the European E-OBS gridded dataset considering the period 1950–2013 and the 0.25°-grid including both study sites (Haylock *et al.* 2008).

Dendroecological Pilot Tree-Ring Study and Fire History

We used a pilot dendroecological study coupled with official fire records from the two sites to generate hypotheses about the fire history of chestnut forests in both municipalities to be tested by future research (Fritts 2001). The reconstruction of fire regimes from available remaining wood is a useful tool to establish past reference conditions by documenting fire occurrence dates over as long a time period as possible (Swetnam *et al.* 1999). Sampled areas were about 1 ha per site and included several chestnut forest patches (1 tree per patch was sampled) where we located all fire-scarred adult chestnuts (n = 12 in Rozas, n = 5 in Casillas; Table 1). The within-site replication corresponds to the multiple sampled trees, which often form small groves, part of hedges, or grow at the front of terraces built near formerly cultivated fields or pastures, particularly in the Casillas site. The sampled size of trees not affected by fire was determined in order to achieve a good within-site replication to obtain a representative chronology or mean series of growth data. Usually, a minimum of 10–15 trees is considered in dendro-chronological studies depending on the cross-dating among trees, which was excellent for both sites (Grissino-Mayer 2001). The growth data for the sampled trees that were not affected by fire will form part of a future study quantifying above ground chestnut biomass and carbon sequestration in both sites.

Cross-sections or partial wedges were removed from visible fire scars – known as "catfaces" and usually an indicator of past surface fire activity – because these enable the examination and dating of fire scars (Arno and Sneck 1977; Van Horne and Fulé 2006). Samples were taken at heights ranging from 0.5 to 1.0 m using a chain saw. To obtain the maximum number of scars from each sample tree, several cross-sections or wedges were taken per individual (perpendicular to the fire scar). This technique did not increase the mortality rate of sampled trees one decade after sampling in similar studies (Heyerdahl and Mckay 2008). Fire-scars were identified by the disruption of growth and subsequent healing patterns of secondary growth as well as charring at the point of injury (McBride 1983). Fire calendar years were determined by cross-dating tree rings in the collected sections (Swetnam and Baisan 1996). To build a site chronology by averaging tree-ring width series from trees apparently not affected by fire we took cores from additional dominant trees (n = 11 in Rozas, n = 18 in Casillas; Table 1) randomly selected in each site and not presenting visible fire scars. Cores were taken at approximately 1.3 m from the ground using an increment borer. All wood samples were air dried, sanded using several papers of successively finer grains until tree-rings were clearly visible and then visually cross-dated. Individual tree-ring width series were measured to the nearest 0.001 mm using a LINTAB semi-automatic measuring device (Rinntech, Heidelberg, Germany). Cross-dating quality was checked using COFECHA (Holmes 1983; Grissino-Mayer 2001).

Lastly, we checked for the presence of anatomical fire-related features (delayed cambial death in the scarred wood region, increase in vessel density, reduction in lumen area of earlywood vessels, formation of tyloses in these vessels) reported by Bigio *et al.* (2010). We analyzed the individual trees showing annual fire scars and also an annual frequency of trees forming scars for each of the two study areas; these can

Table 1 Dendrochronological data and statistics related to fire-scar detection in the two chestnut study areas (Casillas, Rozas) located in central Spain

	Casillas	Rozas
No. trees / radii used to develop tree-ring chronologies	18 / 30	11 / 22
Length of chronology	1860–2013	1908–2013
Mean tree-ring width (mm)	2.80 ± 1.09	4.27 ± 1.17
Mean tree age (years)[1]	110 ± 25	76 ± 23
Length of fire chronology	1934–2013	1923–2013
Number of wood samples used to detect fire scars[2]	16	17
Trees showing fire scars	5	12
Total number of fire scars	17	37
Percentage of years with fire[2]	13.5	36.5
Mean number of years between scars[2]	8.7 ± 2.5	4.4 ± 4.5

Means are given with standard deviation

[1] Estimated as the maximum number of rings counted in cores taken at 1.3 m

[2] These variables were calculated for the best replicated period (1940–2013)

be regarded as a proxy for fire occurrence and extent. Since the number of sampled and cross-dated trees changed through time we applied a correction procedure proposed by Osborn *et al.* (1997) to eliminate variance changes resulting from changing sample replication and to obtain a corrected frequency of trees presenting fire scars.

To validate our fire scar based reconstruction, we compiled data on past fire occurrences from official fire statistics collected from the regional governments of the Castilla y León and Madrid autonomous communities. We obtained individual fire reports for the two municipalities for the period 1984–2009. From these we quantified the fire regime attributes that could be inferred from official fire statistics for the selected sites. These included information on fire regime incidence, size, season and causality. Though the number of sampled trees in our study is low due to the difficulties found in obtaining permits for sampling chestnut trees from multiple small landholders and stakeholders (both sites have "minifundio" land tenure structures), we argue that the data obtained through our pilot dendroecological study are nevertheless useful for the purpose of generating hypotheses on fire regime dynamics to be tested by future more comprehensive studies. This is consistent with adaptive management research methods, which recognize uncertainty and limited information as a persistent feature in ecosystem assessment and management (Rist *et al.* 2013).

Forest Structure Aerial Photo Analyses

Aerial photographs were obtained from the Spanish army's geographical services and included black and white and color photograph series for the years: 1956, 1972, 1985, 2006 and 2011. This allowed for a quantification of the evolution of forest structure in both sites for approximately 60 years (Fig. 3).

To analyze the aerial photographs we placed a grid over the existing cartography for the two municipalities and numbered each grid cell. Using a random number generator, 74 grid cells (plots) were selected for analysis (Rozas $n = 27$, Casillas $n = 47$). Only complete grid cells were analyzed and plots crossing municipal boundaries were discarded. Grid cells including buildings, roads, orchards and other human-made infrastructures were also discarded. Grid cells for the municipality of Casillas covered 5.2 ha while grid cells for Rozas covered 7.3 ha. To visually estimate foliage cover in both sites we used a standardized comparison chart to determine the canopy cover for each grid cell. To describe the forest structure of each grid cell we developed a structure code: no canopy (a), open, mixed-canopy forest (b), closed mixed-canopy forest (c), closed and small-canopy forest (d), open and small-canopy forest (e), open and large-canopy forest (f) and closed and large-canopy forest (g) (Fig. 3). We then assigned a letter to each cell based on a visual estimation of the prevailing forest type. To analyze variations in forest structure from 1956 to 2011 we computed the coefficient of variation for all forest structure types (standard deviation/mean) for each forest type across all intervals in the time sequence.

We used "open canopy" and "no canopy" forest structure types as proxies for evaluating the landscape-level impacts of pre-industrial era traditional landscape management practices which were, and still are, oriented to certain specific forms of land use such as agricultural, pastoral, and chestnut production activities (Seijo *et al.* 2015). "No canopy" structure types, however, can also be a product of deforestation or an interruption in natural forest regeneration processes resulting from increasingly severe forest fires, fires for expanding pastures, grazing by domestic cattle, and/or shifting agricultural cultivation. Therefore, greater caution must be taken in the use of "no canopy" as a proxy for traditional land use than for "open canopy." However, many of the human system drivers conditioning the relative abundance of "no canopy" can also be linked to forest management practices typical of the pre-industrial era.

Finally, from the "Inventario Forestal Nacional" (IFN, Spanish National Forest Inventory) data we were able to describe relative forest species abundance in the two sites and at a regional scale. Data were compiled from two consecutive cycles of the IFN performed within a time interval of 10 years (IFN2 1990; IFN3 2000). For our analysis we summarized volume (m^3 ha^{-1}) for the main tree species to describe their relative abundance in the study sites (Fig. 4). The comparison of the information derived from the plots present in the two sequential IFNs in the study region ($n = 1029$ plots) allowed for an assessment of the growing stock rates of chestnut ($n = 413$ plots).

Fig. 3 Illustrative examples of the evaluated forest structural types : (**a**) open, large canopy (**b**) open mixed canopy (**c**) closed small-canopy

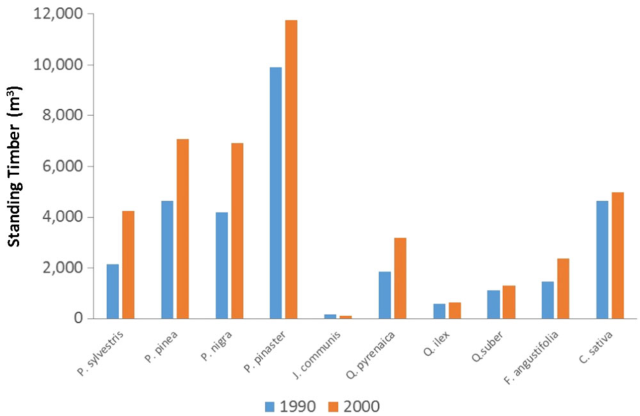


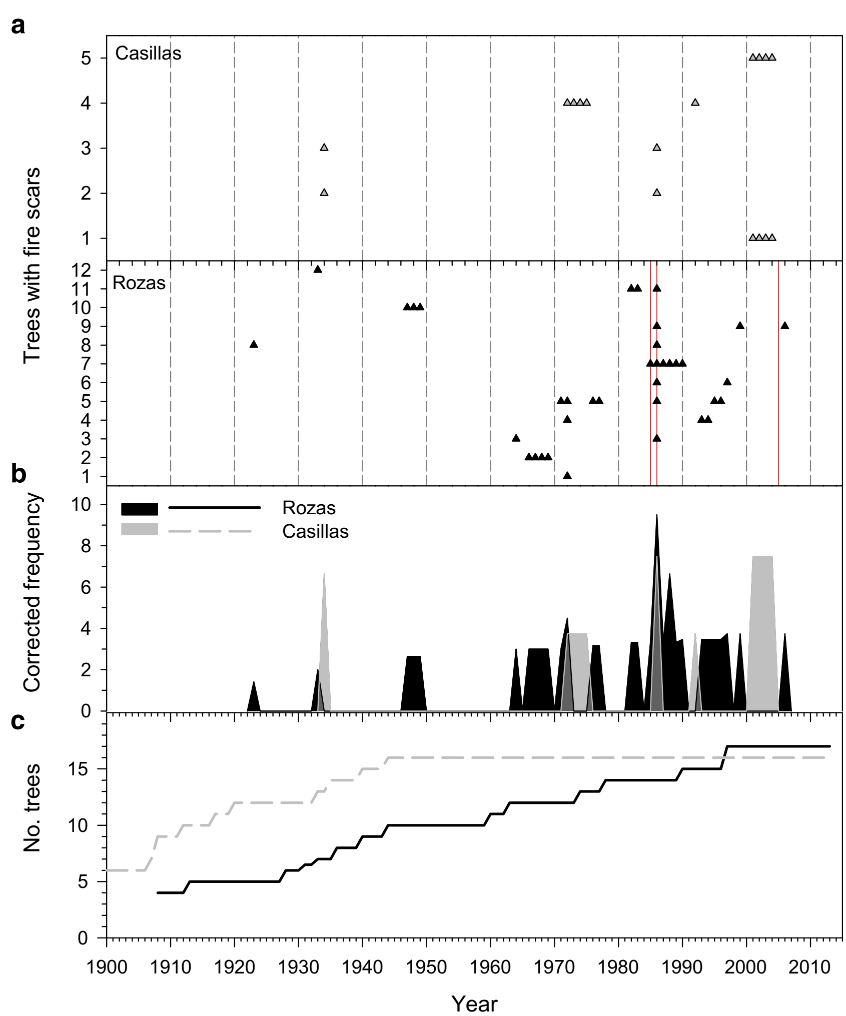
Fig. 4 Tree species abundance in the Casillas and Rozas region according to the IFNThe first five species are conifers (four pines – Pinus sylvestris, P. pinea, P. nigra, P. pinaster– and common juniper – Juniperus communis) and the subsequent species are hardwood tree species (three oak species –Quercus pyrenaica, Q. ilex, Q. suber, narrow-leafed ash –Fraxinus angustifolia–, and chestnut)

Results

Dendroecological Tree-Ring Analysis Pilot Study

A greater number of fire-scars were recorded in Rozas than in Casillas, suggesting a higher incidence of fire events in the former site, particularly since the 1960s (Table 1 and Fig. 5). In both sites landscape fire incidence seems to have increased considerably since the beginning of industrialization in the 1960s. We dated the oldest fire scars to 1934 and 1923 in the Casillas and Rozas study areas respectively (Table 1 and Fig. 5). The mean tree-ring width series (standard chronologies) of both study areas for the best replicated period (1910–2013) are significantly correlated ($r = 0.65$, $P < 0.001$), indicating a common response to climate. Analogously, some years of high fire incidence in both study areas (1965, 1966, 1985, 1986, 1994) according to the fire-scar dates correspond to very dry and hot summers (Fig. 6). Some scars correspond to the 1985 and 1986 fires documented in Rozas, but no scars were observed corresponding to a known 2005 fire. The links between summer climatic conditions and the frequency of

Fig. 5 Trends in estimated fire frequency based on the temporal variability in the presence of fire scars for individual chestnut trees (**a**) and sites (**b**) in the two study areas (Casillas –*grey areas*, Rozas –*black areas*; *dark-grey area* show overlapping frequencies for both study areas). The number of trees assessed to detect fire scars is shown in the *lowermost graph* (**c**). Documented fires in Rozas are indicated by *vertical continuous lines* in the upper figure (**a**).



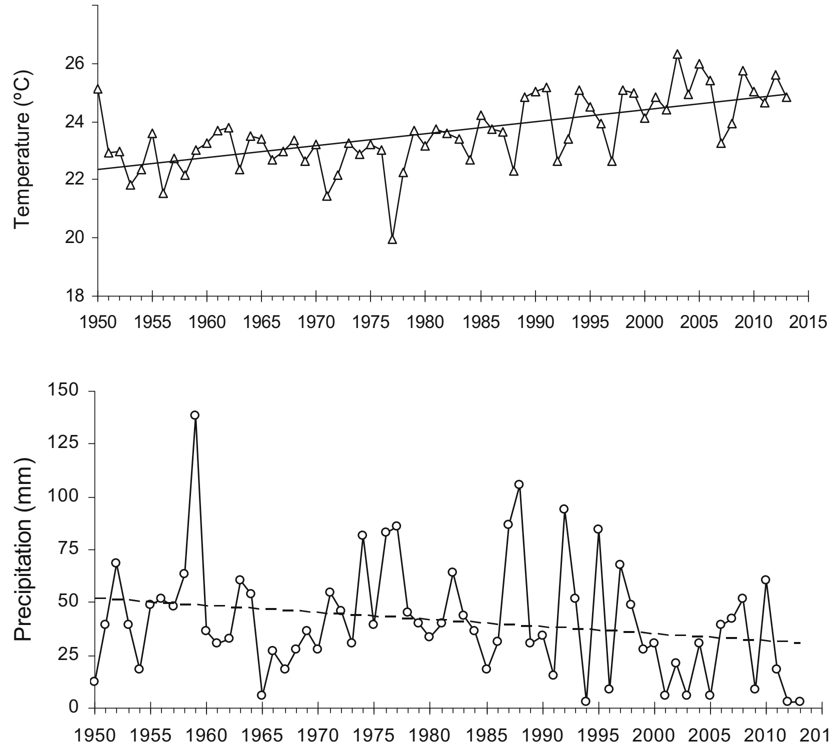


Fig. 6 Trends in summer (June to August) mean temperature and total precipitation in the study area. The linear trends were positive and significant in the case of temperature (slope = + 0.04 °C yr.$^{-1}$, $r = 0.62$, $P < 0.001$) and negative in the case of precipitation (slope = −0.33 mm yr.$^{-1}$, $r = -0.23$, $P = 0.07$)

trees presenting fire scars are most evident in Rozas, where there is a high frequency of fire scars coinciding with dry and hot summers such as those in the mid-1980s and early 1990s. In Casillas, successive fire scars are also related the dry summer conditions of the early 2000s, but we were able to date them only in two trees (Fig. 6).

We found that some sampled trees have fire scars for as many as four or even five consecutive years. We believe that these were probably caused by annual controlled litterfall burning next to or inside the hollow chestnut tree trunk or catface. This is a common practice in TFK-based burning in both sites and is believed by practitioners to prevent root rot (*phytophthora cinnamomi*) infestation in old growth trees (Seijo *et al.* 2015).

Official Fire Statistics

Fire event incidence in official records was greater in Casillas than in Rozas from 1984 to 2009 with the former experiencing 52 fire incidents in contrast to 31 in the latter. Median annual burned areas were similar for both municipalities (Rozas 0.41 ha, Casillas 0.42 ha) but once differences in landscape area are accounted for, burnt surface per year was larger in Rozas than in Casillas by a factor of 10 (2.12 ha km^2 yr.$^{-1}$compared to 0.22 ha km^2 yr.$^{-1}$). Rozas experienced a 1257 ha "large fire" (i.e. official statistical definition: >500 ha) in 1985 whereas none took place in Casillas during that period. In Casillas fires in early spring and autumn months account for a greater proportion (53%) than summer fires (47%). This contrasts with Rozas where summer months account for the vast majority of fire events (71%) with early spring and autumn months seeing far fewer (29%). Some fire scars were associated with years of significantly ($P < 0.05$) warmer temperatures than the 1950–2013 mean in spring (March 1994, April 1986), summer (2005 June) or early fall (1985 September). Several of these fire years recorded no rainfall during winter-spring (1965 April, 1994 March, 2005 January), summer (1986 and 1994 June, 1966 July–August, 1985 and 1994 August) and fall (1985 September–October; Tables 2, 3; Figs 7, 8).

Forest Structure Aerial Photography Analysis

In both sites there has been a gradual reduction in the number of forest structure types when compared to the pre-industrial baseline year of 1960 (Fig. 9). This occurs to a greater extent in Casillas than in Rozas. By 2006, two forest structure types – "closed, large canopy" and "open, small canopy" – disappear from the record in Casillas, while in Rozas the former seems never to have been present and the latter ceases to appear by 1985 (Fig. 9). The "closed, mixed canopy" structure seems to have expanded considerably in both sites, practically doubling in area since 1956. The coefficient of variation is larger for Casillas than Rozas for this forest structure type, suggesting that this process has been taking place there to a larger extent than in the latter site. The "closed, small canopy" structure

Table 2 Temperature in fire years in both sites

Temperature				Fire years					
month	mean	2,50%	97,50%	1965	1966	1985	1986	1994	2005
1	5,91	3,45	8,51	5,02	8,52	3,60	5,33	5,78	5,11
2	7,23	4,51	10,29	4,48	8,83	9,26	6,19	7,01	4,63
3	10,08	6,86	12,77	9,76	8,79	8,40	9,70	12,78	10,36
4	12,34	10,43	15,95	12,55	11,98	12,84	8,59	11,56	13,77
5	16,42	13,03	19,75	18,68	17,09	14,22	18,02	16,46	18,90
6	21,38	17,74	25,23	22,91	19,86	21,42	21,86	22,09	25,42
7	25,00	22,64	27,94	23,24	24,08	25,99	25,66	26,83	26,59
8	24,46	22,37	26,98	24,17	24,14	24,39	23,25	25,64	25,72
9	20,54	16,79	23,28	17,32	21,74	23,86	20,67	18,22	20,51
10	14,98	11,81	17,87	14,81	13,09	16,89	15,59	15,63	15,75
11	9,51	6,89	12,14	8,69	6,73	8,68	9,19	11,22	8,45
12	6,39	3,81	9,53	6,68	5,38	6,11	6,01	7,16	5,93

type has shrunk slightly in Rozas and expanded significantly in Casillas (Table 4).

"Open, large canopy" forest structure has declined in both landscapes overall, although again the coefficient of variation suggests that this process has taken place to a greater extent in Casillas than Rozas. Finally, "no canopy" structure – which can be interpreted as a proxy for agricultural and pastoral land uses in both sites (see below) – declined considerably in Rozas from 1956 to 1985, though it seems to have been slightly expanding ever since. The area of "no canopy" has remained more or less constant over time, declining slightly between 1956 and 1972 and expanding or remaining stable ever since in both sites (Table 4).

As "open canopy" forest structure is more likely to be a proxy of traditional pre-industrial chestnut management for nut production, we diachronically contrasted change in "open" versus "closed" canopy forest structure since the beginning of the industrialization process in the 1960s with the 1960 pre-industrial era baseline year (Fig. 10). Conversely, "closed canopy" forest structure seems to be linked with "rural abandonment," the establishment of recreational hunting estates, industrial era chestnut timber plantations and a decline in both traditional agricultural and silvo-pastoral activities.

"Open canopy" forest dominated the landscape in 1956 in both municipalities (Fig. 10). Since then "open canopy" structure has declined while "closed canopy" structure has expanded, although this process seems to have taken place to a greater extent in Rozas than in Casillas. Finally, to evaluate the possible impact on forest structure of the large fire (>500 ha) that took place in Rozas in 1985 we used Casillas as a control site (no large fires have taken place in Casillas since official fire statistics began for the area). We find that "no canopy," "closed, mixed canopy," and "open, large canopy" structures have expanded since the 1985 fire in Rozas, while "closed, small canopy" types seem to have contracted. In Casillas, the opposite trends are observed after 1985, with the exception of "closed, mixed canopy" structure which, as in Rozas, seems to have slightly expanded. All forest structures measured through aerial photography correspond to the tree species described in the IFN data, which indicate an increase in pine tree volume and a slight expansion of some oak species (*Quercus pyrenaica*) as well as chestnut (Fig. 4).

Table 3 Precipitation in fire years for both sites

Precipitation				Fire years					
month	mean	2,50%	97,50%	1965	1966	1985	1986	1994	2005
1	0,93	0,00	2,68	0,70	1,80	1,40	0,20	0,70	0,00
2	1,02	0,00	2,85	1,20	1,90	1,10	1,70	1,10	1,30
3	0,85	0,00	2,51	1,50	0,10	0,10	0,60	0,00	0,30
4	1,18	0,10	2,58	0,10	1,60	1,10	1,40	0,70	0,40
5	1,15	0,12	3,21	0,30	0,70	0,90	0,20	1,60	0,30
6	0,73	0,00	2,15	0,10	0,90	0,50	0,00	0,00	0,10
7	0,24	0,00	1,19	0,10	0,00	0,10	0,20	0,10	0,00
8	0,30	0,00	1,44	0,00	0,00	0,00	0,60	0,00	0,10
9	0,76	0,00	2,76	1,50	1,00	0,00	1,30	0,60	0,10
10	1,30	0,00	3,79	1,50	2,60	0,00	2,60	1,00	2,50
11	1,32	0,10	3,89	1,60	1,60	1,00	0,50	1,00	1,40
12	1,17	0,00	3,69	1,00	0,00	2,10	0,40	0,40	0,60

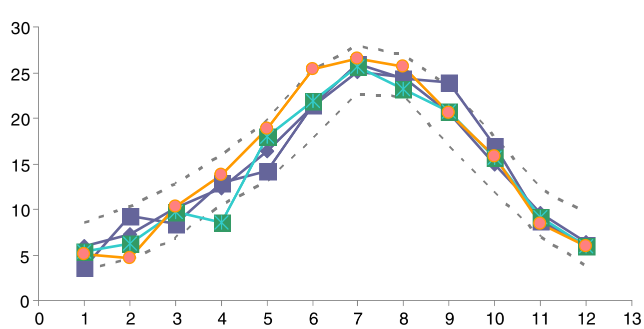


Fig. 7 Climatic drivers of changing fire regimes in Casillas and Rozas: Temperature

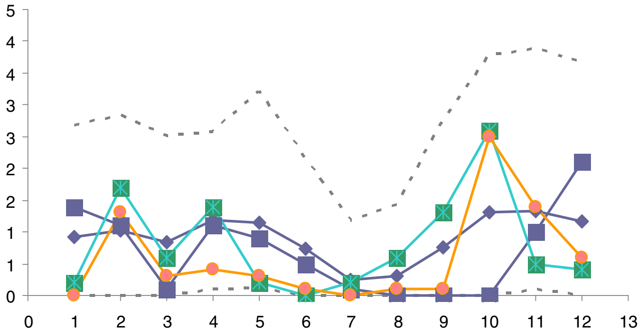


Fig. 8 Climatic drivers of changing fire regimes in Casillas and Rozas: Precipitation

Discussion

Fire Regime Dynamics since Industrialization

Our findings suggest that fire regime attributes may have changed substantially in both Casillas and Rozas since the beginning of industrialization in the 1960s. According to our dendroecological pilot study data, fire incidence in particular seems to have increased in both sites since the 1960 pre-industrial era baseline. This matches the results of other studies on fire frequency conducted elsewhere in Spain. Pausas and Fernandez-Muñoz (2012) hypothesize based on these data that before the 1960s fire regimes in the Western Mediterranean were fuel-limited because of intensive land use by rural local communities. In the past, extensive animal husbandry, shifting agricultural cultivation, and firewood logging kept landscape fuels to a minimum and fire spread was inhibited. Consistent with this hypothesis, landscape fuels in both our study sites seem to have expanded considerably in recent times. According to the forest inventory data, pine species have increased considerably since the 1990s as well as mixed oak-chestnut stands (though to a much lesser extent; Fig. 4). This development could be the consequence of state foresters selecting pine species for afforestation and industrial uses

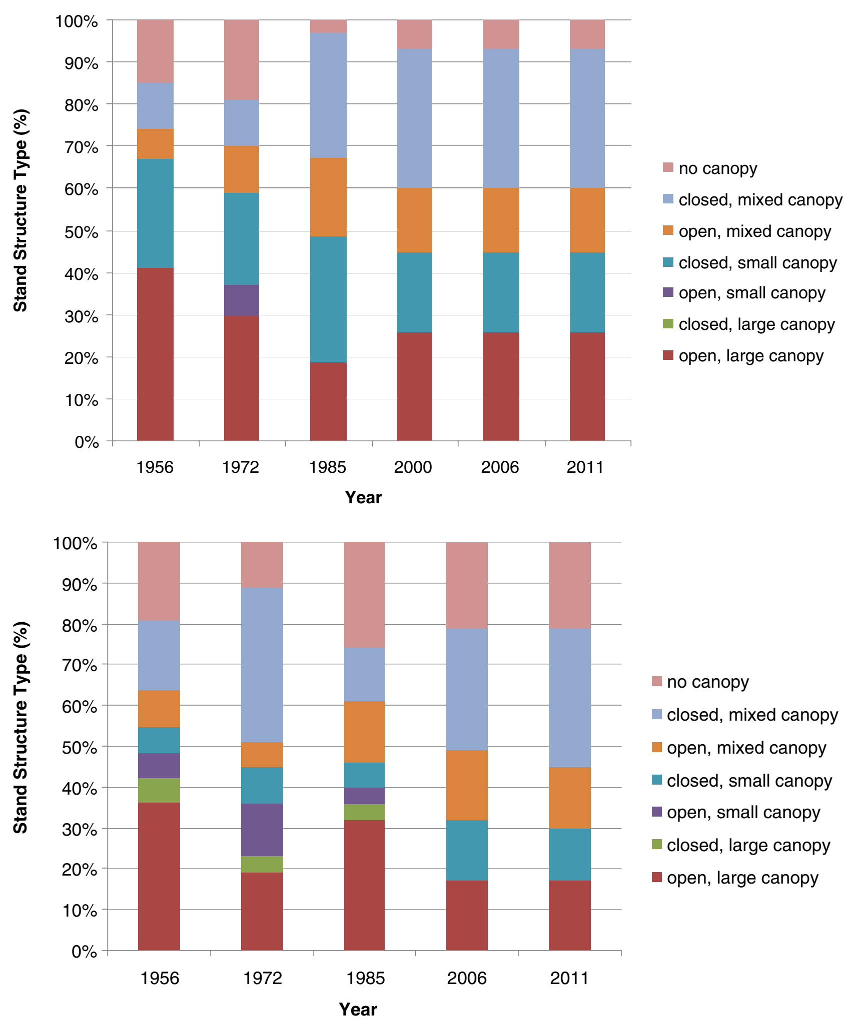


Fig. 9 Changes in the abundance of forest structure types in Rozas (**a**) and Casillas (**b**) study areas from 1956 to 2011

Table 4 Changes over time in stand structure during the 1956–2011 period. The numbers correspond to coefficient of variations (in %) of all stand types analyzed in the two study areas, Casillas and Rozas (see also Figs. 8 and 9)

Stand type	Study area	
	Casillas	Rozas
Open large canopy	33.60	25.44
Open small canopy	40.82	178.85
Open mixed canopy	15.05	13.61
Closed small canopy	35.57	18.36
Closed mixed canopy	36.84	43.81
No canopy	24.89	57.54

(e.g., resin tapping) since the 1960s in Spain, and to the expansion of pioneer pine species in formerly cultivated areas and fire-disturbed sites (Stephens *et al.* 2014). In addition, mixed oak-chestnut stands characterized by closed canopies also seem to be becoming more abundant due to the abandonment of coppicing and firewood logging in many of these mixed stands and because chestnut is shade-tolerant (Camisón *et al.* 2015).

Pausas and Fernandez-Muñoz (2012) also hypothesize that fire regimes in Iberian Peninsula landscapes tend to be increasingly "climate driven" in contrast to the pre-industrial past when fire regimes were "fuel limited." Our pilot study dendroecological data seem to support this hypothesis, though there are some subtle differences and important nuances suggested by our findings that merit further discussion. In particular, the degree to which the fire regime seems to be increasingly coupled with climate in the more economically-developed Rozas site than in the less economically-developed Casillas site. Increased fire regime-climate coupling in Rozas may well be provoked by the larger extent to which closed canopy forest structure, and therefore increased fuels, have expanded in its landscape. More interestingly, fire regime-climate decoupling in Casillas, we hypothesize, may be driven in part by the greater incidence of fire events in the non-vegetative season (October–March). If this were the case (i.e., that fire seasonality linked to TFK-based fire use practices results in increased fire incidence but decreased burnt area), it could be an important finding for fire management in chestnut forest landscapes, since it implies that absolute fire bans – including non-vegetative season TFK-based controlled burns by local communities – could unintentionally lead to more vegetative season fire events with a greater burnt area due perhaps to greater litterfall understory fuel build-up (Pezzatti *et al.* 2013; Seijo *et al.* 2015). According to local community TFK, annual literfall burning as well as controlled low intensity charring with straw or chestnut leaf burns of the inside of the catface of chestnut trees may help prevent *phytophtora cinnamomi* fungal infestation of trees while simultaneously curbing understory fuel accumulation (Seijo *et al.* 2015).

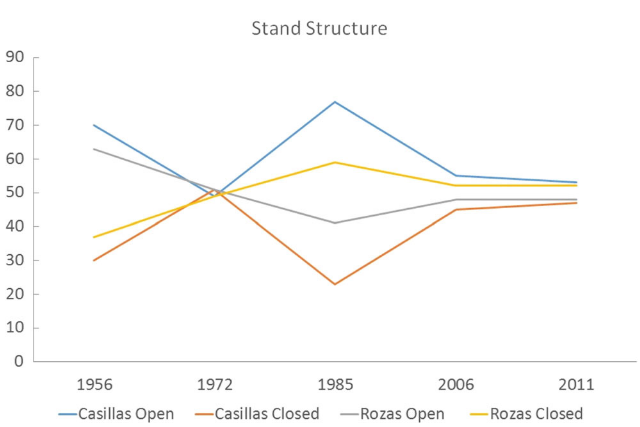


Fig. 10 Changes over time in open vs. closed canopy structure as a % of measured forest structure types

Impact of Evolving Fire Regime Dynamics on Current Forest Structure

In both sites the number of forest structure types has declined since 1960, the pre-industrial era baseline year. Generally speaking, "open canopy" area has diminished and "closed canopy" area has expanded. At present this general trend manifests itself differently in both municipalities' landscapes. "Closed canopy" structure currently dominates the Rozas landscape while in Casillas "open stand" types still occupy most of its forested area (Fig. 10).

Particularly if we consider that "no canopy" area has decreased in Rozas since 1956, according to the aerial photography record, and more specifically since the 1985 large fire, it would seem that for the most part landscape fires are not having an adverse effect on overall forest cover in this more economically developed site. "Open canopy" area in the past (and also in the present, although to different degrees in both sites) seems to be driven by various anthropogenic land use practices typical of the pre-industrial era. Three main practices that were or are still common in these municipalities, particularly in Casillas, are related to the cultivation of cereals, extensive animal husbandry (i.e., free-ranging rather than penned), and, especially, chestnut production. Indeed, TEK studies in the sites have identified at least 14 possible different uses of fire as a TFK-based ecosystem management tool in chestnut forest ecosystems dating back to the pre-industrial era (Seijo *et al.* 2015). In the three traditional forms of land use in the study areas, fire was a crucial cost-effective TEK-based landscape management tool. Indeed, the toponym "Rozas" refers to a type of "slash and burn" shifting agricultural practice common throughout Europe in the pre-industrial era that consisted in manually eradicating all shrubs and small diameter trees growing in fallow fields, burning them in piles, and ploughing the ashes into the soil as fertilizer (Sigaut

1975). The use of fire for pasture regeneration is also considered a traditional land use practice originating in the pre-industrial era, the rationale and techniques of which have been described in the specialized literature (Metailie 1981; Fernandez-Gimenez and Fillat 2012; Coughlan 2014, 2015). More recently, the annual burning of litterfall in old growth chestnut tree groves and the use of the smoke generated as a pesticide to control "root rot" and other pests has also been identified as a pre-industrial TEK-based era practice (Seijo *et al.* 2015).

Our analysis suggests that fire use based on pre-industrial era TFK has been steadily declining in both sites, though this decline seems to have been sharper in Rozas than in Casillas (to the extent that "open canopy" forest structures still dominate the latter's landscape). This hypothesis is further reinforced by the official fire statistics and our pilot dendroecological study as well as the IFN data (Figs 4, 5). In particular, official fire statistics seem to indicate that fire incidence is greater in Casillas than in Rozas which, in turn, would suggest that wildfire incidents in Casillas are more closely linked to accidental escapes taking place in the traditional annual seasonal pile burning of chestnut leaves and litterfall (Seijo *et al.* 2015).

In sum, our preliminary findings suggest that pre-industrial era type fire use seems to be more common today in Casillas than in Rozas and could possibly be positively feeding back to limit fire spread and burnt area with current forest structure in Casillas where "open canopy" forest structures still dominate the landscape and therefore the fire regime is more "fuel limited" (Pausas and Fernandez-Muñoz 2012). This process could also be related to the looser implementation of fire exclusion policies on the part of the regional government of Castilla y León in Casillas, possibly due to lower budgets (see above). However, additional research in different chestnut forest landscapes with uneven levels of economic development and fire exclusion policy implementation throughout the Mediterranean basin would be needed to further test this hypothesis and confirm these findings.

Historical Range of Variability

The implications for future fire management of transformed fire regimes in MTEs can be evaluated with the aid of the Historical Range of Variability (HRV) concept (Morgan *et al.* 1994). HRV can be defined as "the estimated range of some ecological condition that occurred in the past" (Duncan *et al.* 2010: 5). Suggesting ways in which the HRV for chestnut forests can be defined and measured has important implications for the management of chestnut MTEs throughout the Mediterranean Basin where these landscapes face an uncertain future (Conedera *et al.* 2004).

Unfortunately, our dendroecological pilot study includes only two landscapes and is not extensive enough to fully characterize the historical fire regime in chestnut forest ecosystems by determining the extent to which current fire events are "uncharacteristic" based on a "condition class" classification (Hardy *et al.* 2001). More chestnut forest fire histories with a larger number of samples and in different landscapes and locations would be needed to complete this work. However, based on our pilot study findings, some preliminary hypotheses for future research can be identified.

A simple criterion for determining "uncharacteristic" fires that depart from HRV has been proposed by Huffman (2013), who argues that the decoupling of fire events from their traditional agro-ecological community type can be used as an indicator of shifts in HRV. This is in agreement with previous criteria outlined in review articles of HRV and "edge effects" by other fire ecologists (Keane *et al.* 2009; Gill *et al.* 2014). If Huffman's criteria are used to determine HRV in chestnut MTEs both Casillas and Rozas would seem now to be experiencing fire incidents that do not fit with the historical pre-industrial fire regime. If we take into account, for instance, seasonality as a key fire regime attribute, many recent fire events in both municipalities no longer seem to correspond with traditional agro-ecological type fires or their season, although again, this seems to be taking place to a greater extent in the more economically developed Rozas site. In addition, if we transpose the "megafire" triangle drivers (Fig.2) to specific documented developments in the CHANS of Rozas and Casillas, we can see that in all likelihood many of the biophysical trends identified in both sites will continue and intensify in the near future. This may translate specifically into an increased probability that larger and more severe fires will take place in these landscapes similar to the "large fire" of 1985 Rozas. In particular, present climate forcing of the local fire regimes – as exemplified in higher summer temperatures and lower precipitation (Figs 6, 7, 8) – will likely continue as a result of climate change trends. According to our results and the existing literature, this again may be linked to increased fire incidence (Pausas 2004; IPCC 2014). This is a hypothesis to be quantitatively tested by future research into similar unevenly developed and divergently fire-managed chestnut MTE sites throughout the Mediterranean basin.

Finally, when considering the two other elements of the "megafire" triangle – fuel loads and human ignitions – we have seen that traditional pre-industrial era TFK-based burning seems to be diminishing in both landscapes. This is a result not only of active state fire-exclusion policies but also as a side-effect of rural abandonment, an increase in forest cover (particularly conifers) due to industrial era state afforestation policies, changes from an "open" to a "closed canopy" forest structure, and a relative decline and aging in the populations of both municipalities (Fig. 11).

Indeed, older generational cohorts generally have a greater familiarity with TEK-TFK-based practices (Seijo *et al.* 2015). As this generation dies it would be reasonable to assume that traditional fire practices will also gradually disappear with

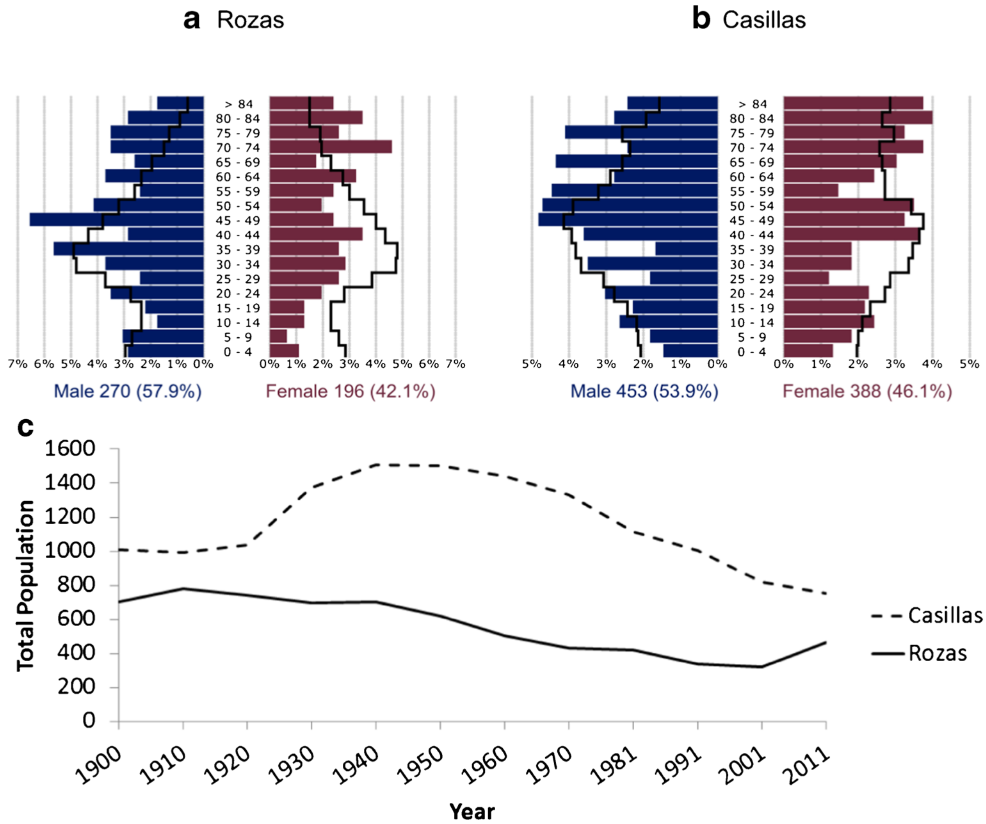


Fig. 11 Demographic evolution Casillas and Rozas since the beginning of industrialization 1950–2011 (Caja España 2012). Solid line indicates the average for the provinces of Avila and Madrid, where the municipalities are located respectively, as a whole

them (unless there is an active programme of communication of TEK-TFK practices to younger people). Present depopulation trends will result not only in fewer people overall in these rural landscapes to manage chestnut forest ecosystems, but also fewer people who know how to manage them with TEK-TFK practices. Therefore chestnut forests in Casillas and Rozas may already be well on their way to reaching two parallel "tipping points;" one affecting the human system (a declining, older, TEK-TFK-savvy rural population) and another one affecting the natural system (a more "closed canopy" type forest structure). Forest species composition is, in addition, evolving towards more fuel abundant fire-prone pine forests and denser, mixed closed-canopy forest structures formed by oak species (*Quercus pyrenaica*) and chestnut, which are directly in the former and indirectly in the latter a consequence of state-led forest industrialization strategies at a state-wide level. Again, further studies in other chestnut MTEs would be needed to confirm whether this is a common trend throughout the Mediterranean basin.

Implications for Climate Change Adaptation Strategies in Chestnut Forest Ecosystems

Based on our preliminary findings, summed up in the transposition of the "megafire" triangle to local conditions in our study sites, it would seem that fire-exclusion policies have failed to curtail the trend towards larger fires in Rozas in spite of a generously funded implementation. This is particularly clear when compared with the policy of relative tolerance for traditional TFK-based fire management practices in Casillas. Greater fire incidence in the non-vegetative season in Casillas may be resulting in less severe and smaller wildfires for chestnut tree forest ecosystems in the summer, perhaps because of the preservation of more "open canopy" forest due to annual traditional burning of litterfall. On the other hand, fire exclusion policies – which have been more strictly implemented in Rozas – seem to have had only a minor influence on fire incidence - as reflected in official fire statistics - but not in fire spread and burnt area, which is much larger for this municipality. In contrast, climate drivers appear to be relatively similar for both sites (Figs 6, 7, 8).

Again, further research into other unevenly developed and divergently fire managed chestnut forest sites throughout the Mediterranean Basin would be needed in order to further test this hypothesis. In light of this limited evidence, the best adaptation strategy for a changing climate in chestnut landscapes might be based on controlled or prescribed burning by either local communities or trained professional fire managers. This conclusion seems to be supported by the data from our pilot dendro-ecological study and has been suggested recently by other authors (e.g., Khabarov *et al.* 2016; Moreira and Fernandes 2015). If this were the case, perhaps the TFK-based techniques used by local community fire practitioners in Casillas and Rozas could prove useful for the development of prescribed burning plans (as Fernandes *et al.* (2013) have suggested for other locations).

Not only is there much to be learned from the burning techniques, ecological goals, and seasonal timing with which TFK-based traditional burns continue to be performed in both sites, but governmental authorities could also possibly find it useful to allow local communities to continue these practices as the most cost-effective fire management policy in chestnut MTE landscapes. Local communities in Casillas and Rozas already have the knowledge and the economic incentives – including chestnut production and extensive animal husbandry – to carry out TFK-based burning without the need for passing on these costs to the state administration. This strategy may not always be possible in the immediate future, however, as rural populations decline and, particularly, as the older generational cohorts that are more familiar with these traditional practices dies.

Easier access to TFK based fire use for local communities could also contribute to chestnut production profitability and, thus, an increased viability for the local economies in these municipalities. All technological alternatives to fire use for the main rural productive activities existing at present (chemical fertilizers for pasture regeneration, externally produced industrial feed for livestock, prescribed burning for fuel control) are generally more costly than timely controlled burns implemented by local community stakeholders. Furthermore, these alternatives are at least as politically and ecologically controversial. Stronger local economies could in turn also help forestall rural abandonment, one of the leading CHANS feedbacks identified in the literature driving current fire regime changes in MTEs (Millington *et al.* 2007; Pausas and Fernandez-Muñoz 2012; Fernandes *et al.* 2013).

Conclusions

Fire regimes in chestnut forests located in central Spain seem to have changed considerably since the beginning of industrialization in the 1960s. As we have hypothesized in this pilot study, the transformations in these MTEs may be driven by the triangle of drivers formed by a decline in TFK-based burning practices, the stricter implementation of state fire exclusion policies, and climate change. In this study, we suggest that non-vegetative season, annual litterfall burning may help prevent the increases in fuel loads and changes in forest structure that may be contributing to larger fires. On the basis of our findings, we hypothesize that a management policy based on prescribed burning informed by the techniques and ecological goals of TFK-based burning by local communities may be a more adequate adaptation strategy to climate change than the strict fire exclusion policies carried out at present. These hypotheses need to be tested, however, by further research into unevenly developed and divergently fire managed chestnut forest landscapes throughout the Mediterranean basin.

Acknowledgements This research was made possible by an Academic Outreach Engagement Grant from Middlebury College. F. Seijo would like to thank the municipal governments of Rozas de Puerto Real and Casillas - and particularly David Saugar and Daniel Moreno - for their kind and disinterested collaboration in the implementation of this research project. FS would also like to express his gratitude to Peter Fulé (Northern Arizona University) and Beatriz Pérez Ramos (Universidad de Castilla-La Mancha) for their help in obtaining the official fire statistics for Casillas, and to Captain Jorge García Rodriguez (Spanish Army) for facilitating us access to aerial photographs. Middlebury College, Swarthmore and Pomona students Jacqueline Wyard-Yates, George Lampe, Nathaniel Truman and Heidi Yuan also contributed valuable insights for this study. J. Millington would like to acknowledge the Leverhulme Trust for his Early Career Fellowship, which funded his fieldwork in the study area. G. Sangüesa-Barreda's and J.J. Camarero' contributions to this study were supported by projects CGL2011-26654 (Spanish Ministry of Economy and Competitiveness).

Compliance with Ethical Standards The authors declare that they have no conflict of interest.

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