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Disentangling the relative role of climate change on tree growth in an extreme Mediterranean environment

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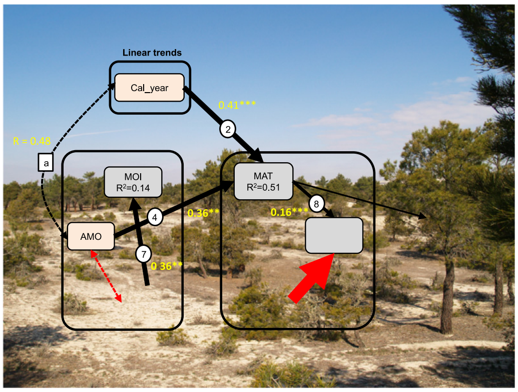
HIGHLIGHTS

- The NAO and the AMO are the most important climatic drivers of growth.
- Climate warming represents one third of the climatic variability in this area.
- Climate warming has had a net positive influence on tree growth.
- There is no evidence of precipitation tendencies or carbon fertilization.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change can impair ecosystem functions and services in extensive dry forests worldwide. However, attribution of climate change impacts on tree growth and forest productivity is challenging due to multiple inter-annual patterns of climatic variability associated with atmospheric and oceanic circulations. Moreover, growth responses to rising atmospheric CO_2, namely carbon fertilization, as well as size ontogenetic changes can obscure the climate change signature as well. Here we apply Structural Equation Models (SEM) to investigate the relative role of climate change on tree growth in an extreme Mediterranean environment (i.e., extreme in terms of the combination of sandy-unconsolidated soils and climatic aridity). Specifically, we analyzed potential direct and indirect pathways by which different sources of climatic variability (i.e. warming and precipitation trends, the North Atlantic Oscillation, [NAO]; the Mediterranean Oscillation, [MOI]; the Atlantic Mediterranean Oscillation, [AMO]) affect aridity through their control on local climate (in terms of mean annual temperature and total annual precipitation), and subsequently tree productivity, in terms of basal area increments (BAI). Our results support the predominant role of Diameter at Breast Height (DHB) as the main growth driver. In terms of climate, NAO and AMO are the most important drivers of tree growth through their control of aridity (via effects of precipitation and temperature, respectively). Furthermore and contrary to current expectations, our findings also

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support a net positive role of climate warming on growth over the last 50 years and suggest that impacts of climate warming should be evaluated considering multi-annual and multi-decadal periods of local climate defined by atmospheric and oceanic circulation in the North Atlantic.

1. Introduction

Anthropogenic emissions of greenhouse gases, as a major forcing of the contemporaneous climate warming and the ensuing rise in aridity (IPCC, 2013), can impair ecosystem functions and services in extensive, water-limited forest biomes worldwide (Dale et al., 2001). In the Mediterranean basin, in particular, climate change may compromise severely forest functioning due to increased aridity and drought intensity (Lindner et al., 2010). At a regional level, however, warming and changing precipitation patterns are also tied to periodic oscillations in atmospheric and oceanic circulations (Wang and Schimel, 2003; Cohen and Barlow, 2005; Sutton and Hodson, 2007). Therefore, a proper attribution of changes in forest productivity to climate change impacts demands a proper identification of the relative roles of warming on the one hand and sources of inter-annual climatic and non-climatic variability on tree growth on the other hand, i.e., a hierarchy of direct and indirect influences operating on tree growth at several scales and levels of organization from region to tree-level (Galván et al., 2012).

The influence of atmospheric/oceanic circulations on local climatic variability is well known in the North Atlantic region (Marshall et al., 2001). For instance, local precipitation in western Europe is closely associated with periodic changes in atmospheric pressure at sea-surface level between the Azores high and the Iceland low, also known as the North Atlantic Oscillation (NAO, Trigo et al., 2002). This fact has allowed correlating the NAO with several biological processes in Europe, including plant reproduction and masting (Bravo et al., 2017; Fernández-Martínez et al., 2017), tree growth (Rozas et al., 2009; Camarero et al., 2013; Dorado-Liñán et al., 2017), or animal behavior (Hüppop and Hüppop, 2003). Another important climatic pattern in the northern hemisphere is associated with the sea surface overheating oscillations in extratropical latitudes in the North Atlantic Ocean. This phenomenon is known as the Atlantic Multidecadal Oscillation (AMO), and similar to the NAO, leaves a signature in long-term growth records of long-lived organisms such as trees and corals (Gray et al., 2004; Hetzinger et al., 2008; Wang et al., 2011). Additionally, in Mediterranean regions of Europe, other modes of natural variability may influence net primary productivity. For instance, the Mediterranean Oscillation (expressed as the Mediterranean Oscillation Index, or MOI), defined as the atmospheric mass dipole between Algiers and El Cairo, is known to influence precipitation regimes in the Mediterranean Basin (Conte et al., 1989). In general, all these sources of variability control primary climatic elements (i.e. annual precipitation and mean annual temperature), the associated climatic aridity defined in terms of the ratio precipitation/evapotranspiration (sensu United Nations Environmental Programme definition, UNEP, 1992), and drought as periods of abnormally intense water deficit. Tree growth and forest productivity in the western Mediterranean are therefore potential subsidiaries of atmospheric and oceanic circulation influences (Camarero, 2011; Rozas et al., 2009).

Besides climate, other exogenous and endogenous factors at the level of individual trees may leave mid- to long-term signatures in tree productivity, especially in water-limited ecosystems. On the one hand, the rise in atmospheric CO_2 can enhance tree productivity through increased carboxylation and enhanced water use efficiency (Keenan et al., 2011). On the other hand, tree growth is conditioned by ontogenetic developmental changes associated with size and age (Wyckoff and Clark, 2005). In this context, attribution of tree growth trends to climate change impacts is troublesome. Conveniently managed, linear trends such as warming might be isolated from other growth determinants such as tree size or CO_2 by using a straightforward conceptual outline defined in the form of structured equations (Grace, 2006; Shipley, 2016). In other words, complex relationships can be split up into direct and indirect relationships in the frame of a theoretical scheme.

Here we aim at disentangling the relative roles of climate change and modes of climatic variability on tree growth by controlling aridity via temperature and annual precipitation. Using tree-ring widths (TRW) and Structural Equation Models (SEM), we define a hierarchical framework to study tree growth responses to climatic (i.e., climate change and natural climatic modes of variability) and non-climatic factors (i.e., tree size) over the last 50 years in individual pine trees. To this end, we select an extremely dry Mediterranean environment as a representative case study of extensive dry forests at the edge (sensu Hampe and Petit, 2005), which are expected to be highly vulnerable to climate change impacts and thus can be used as early warnings in the coming decades (see examples in Mátyás and Sun, 2014; Corona et al., 2015; Sánchez-Salguero et al., 2017). We hypothesize that tree growth is (i) directly driven by local climatic conditions (namely precipitation, mean temperature, and aridity), global change drivers (i.e., carbon fertilization), and tree endogenous determinants (i.e., tree size); and (ii) indirectly through climate change and global atmospheric-oceanic circulation via local climatic conditions. As climatic modes depict oscillations composed of phase/antiphase periods which together last from a few years to a few decades, they might be distinguished from climate change in that the later typically depict a non-oscillating linear/exponential trend over the last century (Pretzsch et al., 2014). Thus, tree growth is a result of a hierarchical combination of climatic influences in addition to other, non-climatic determinants such as tree size. Specifically potential climate change constraints on tree growth are contingent upon atmospheric and oceanic circulation states, and thus, vulnerability to climate change will depend on climatic events (e.g., periods of intense/frequent droughts or cooling conditions) associated with climate modes coupling (Camarero, 2011; Dorado-Liñán et al., 2017; Madrigal-González et al., 2017). The understanding of these processes and anticipation of these periods is of paramount importance for forest adaptation in order to maintain ecosystem function under increasingly arid conditions.

2. Materials and methods

2.1. Study area

The study was conducted in an extreme environment of the central Iberian Peninsula (41°22′11″ N; 4°15′22″ W). We selected this unique environment because strong climatic-edaphic constraints make it a good reference for early warnings of climate change impacts and risks on forest productivity in the Mediterranean. Besides, this forest has a long tradition of management (i.e. shelterwood thinning and resin tapping) that still today provides important economic resources to the rural community (Soliño et al., 2018). For practical purposes, we selected non-tapped pine trees to avoid wood anatomical alterations that might have affected tree-ring measurements otherwise. Moreover, we considered a protected section of the forest where thinning was highly restricted in the past, so as to conduct the sampling in an area for which the influences of thinning and selviculture is smallest.

The selected forest grows in a flat area with predominance of dunes at elevations ranging from 805 to 810 m a.s.l. Soils are sandy, highly unconsolidated and very poor in organic matter (see Gómez-Sanz and García-Viñas, 2011 for more details). Mean annual temperature is 12 °C and annual precipitation oscillates between 430 and 470 mm, with maximum rainfall pulses recorded during late August and spring, as typical for a Mediterranean-type climate. Winters are cold as a result of the high continental influence, whereas summers, locally extending for 4–5 months from June through September–October, are dry and warm. The natural vegetation at the study site is composed of a rich herbaceous plant layer (mostly ephemeral plant species) and few *chamaephytes* such as *Helichrysum stoechas* or *Thymus mastichina*. The dominant tree species is *Pinus pinaster* Aiton; it shows a scattered distribution across the dunes. Due to the combination of extreme edaphic and climatic conditions, tree individuals do not exceed heights of 4–7 m in the healthiest individuals. Many tree individuals, however, have a shrubby appearance with a maximum height of 2 m or less, presumably reflecting irreversible damage during early development stages under extremely dry conditions (Fig. 1).

2.2. Tree ring data

Overall, 32 *P. pinaster* individuals were sampled in an area of 25 ha in December 2012. We randomly chose trees of different size to account for the size structure of the population. We discarded trees with a shrubby appearance due to the difficulty to read growth rings properly and hence to date them correctly. In each sampled tree, we measured the trunk diameter and obtained two cores at a height of ca. 30–40 cm above the ground with an increment borer. After field sampling, cores were air-dried and then glued on woody supports. All samples were polished using sand paper of three different grains (i.e., 80, 320, 600 grit) and scanned at 1000 dpi resolution (Scanjet 300, HP®) for further measurements. We used the Image J software (Schneider et al., 2012) to measure rings at millimeter scale with two decimal positions. Subsequently, the two series obtained for every tree were cross-dated using pointer years as a reference of signals that are common to the majority of tree individuals (Yamaguchi, 1991). To ensure a sufficient

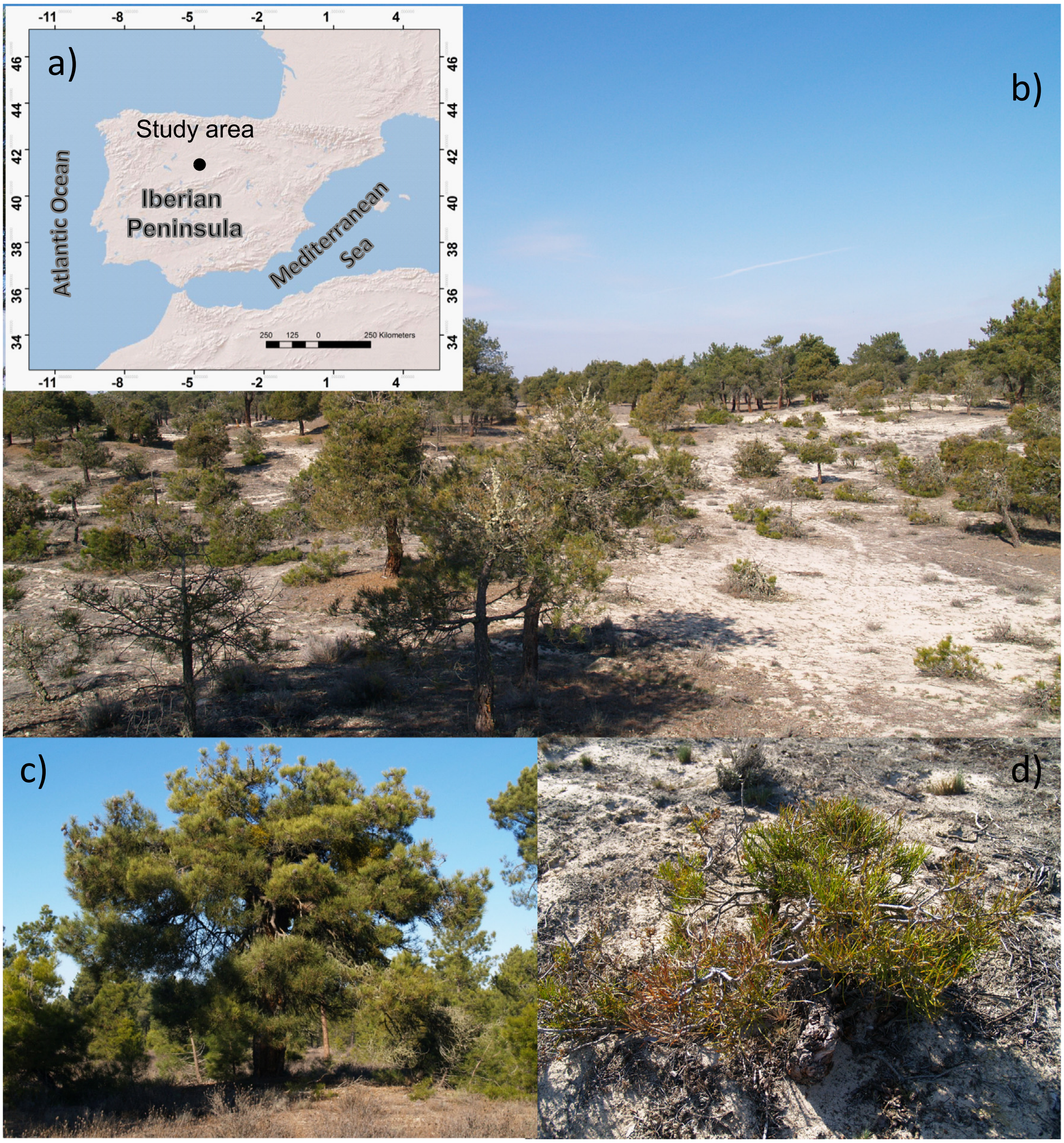

Fig. 1. (a) Geographical location of the study site overlaid on a (B) landscape image of the study area showing the poor/severe environment in the inner dunes. Detail of (c) healthy and (d) unhealthy individuals.

number of trees for later statistical analyses, we set the initial year of this study in 1962 (9 tree individuals; Fig. 2) with a time window analyzed of 50 years until 2011.

We then reconstructed annual trunk diameters for each individual tree by discounting tree-ring widths backwards. Thereafter, we assessed the corresponding Basal Area (BA) for every single year by applying the formula:

$$BA = \frac{\pi}{4} * d^2$$

Finally, we expressed annual radial growth as a Basal Area Increment (BAI) in mm^2 as the difference between basal areas of consecutive years (Biondi et al., 1994).

2.3. Climatic data

For the climate analysis, we used those climatic indices which reportedly have the largest influence on weather and climate in the central regions of the Iberian Peninsula (Trigo et al., 2002; Martin-Vide and Lopez-Bustins, 2006), namely the North Atlantic Oscillation (NAO), the Atlantic Multidecadal Oscillation (AMO) and the two Mediterranean Oscillations, i.e. (1) the Mediterranean Oscillation Index (MOI, Palutikof et al., 1996), and the (2) Western Mediterranean Oscillation Index (WeMOI, Martin-Vide and Lopez-Bustins, 2006). The NAO index is defined as the difference in pressure between Iceland and Gibraltar (Hurrell, 1996) and was retrieved from http://www.cru.uea.ac.uk. The AMO index represents the variability of North Atlantic sea-surface temperatures (SST) (Sutton and Hodson, 2007) and is computed as an area-weighted averaged SST from the Kaplan SST V2 dataset over the North Atlantic (0–70°N); the datasets used to analyze AMO were retrieved from http://www.esrl.noaa.gov/. The MOI index is defined as the normalized pressure difference between Algiers and Cairo and is based on NCEP/NCAR reanalysis data (Palutikof et al., 1996). The WeMOI is defined as the difference of the standardized values in surface atmospheric pressure in San Fernando (Spain) and Padua (Italy) (Martin-Vide and Lopez-Bustins, 2006); data for the assessment of the MOI was retrieved from https://crudata.uea.ac.uk/cru/data/moi/; data for the assessment of the WeMOI was retrieved from http://www.ub.edu/gc/en/2016/06/08/wemo/.

We computed mean annual temperature (MAT) and annual total precipitation (AP) as the average of temperature and precipitation records, respectively, from the two nearest meteorological stations (National Agency for Meteorology in Spain, AEMET): Valladolid (51 km northwards) and Segovia (50 km southwards). Annual climatic data were computed from September of the previous year to August of the present year to account for the influence of previous winter conditions on the current growing season (Rozas et al., 2009; Bogino and Bravo, 2008). The aridity index of UNEP was computed as follows (UNEP, 1992):

$$Aridity = \frac{AP}{PET}$$

where AP is the annual total precipitation (September of the previous year to August of the present year) and PET is the potential evapotranspiration index following Thornthwaite (1948).

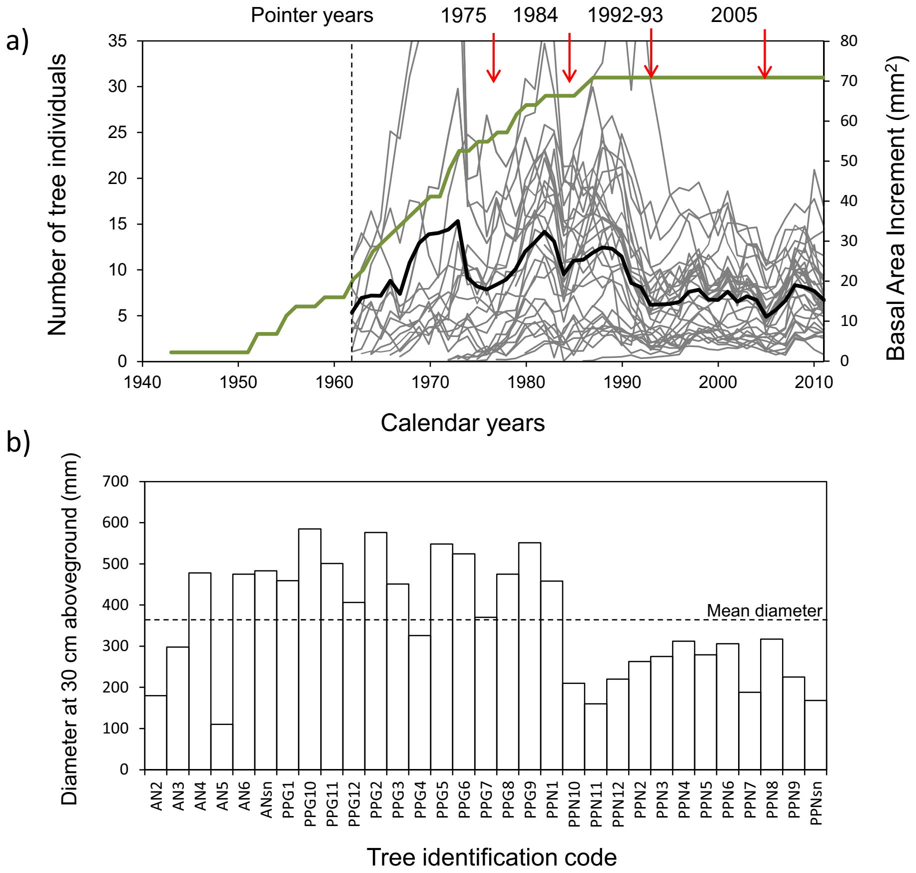

Fig. 2. (a) Growth chronologies of individual trees (grey lines) and mean chronology (black line) of *P. pinaster* growth for the period 1962–2010. The thick solid grey line indicates the cumulative number of tree chronologies available for analyses. Red arrows indicate negative pointer years used to cross-date individual growth series. (b) Distribution of diameters at breast height of the sampled trees. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4. Data analyses

The signature of the physical environment on tree growth can reportedly be obscured by individual-level determinants such as tree size or tree age (De Luis et al., 2009; Carrer, 2011). Here we use non-detrended individual growth series as these are considered to provide a more complex and much more complete picture of growth patterns in a given population (Biondi and Qeadan, 2008). From a purely ecological perspective, individual-based analyses may, thus, provide a more realistic notion of tree performance by including individual-level factors such as tree size or age (Carrer, 2011).

We used SEM to unravel direct and indirect effects of climate change (i.e., climate warming and reduced AP) and other global change trends (i.e., carbon fertilization and enhanced water use efficiency due to rising atmospheric CO_2) on BAI at the tree level. SEMs allow approaching to causal models through the exploration of complex, direct and indirect relationships between interrelated variables (Grace, 2006). We firstly created a SEM using a potential set of interconnected regression analyses in which arrows departing from the calendar years (linear temporal trends) represent the abovementioned global-change hypotheses. This initial model included BAI, aridity, MAT, AP, and MOI as endogenous variables in five regression analyses respectively (see supporting literature for all these hypothesis in Table 1): (i) growth as function of size, estimated as Diameter at Breast Height (DBH, in log form), aridity, MAT and calendar years (carbon fertilization hypothesis); (ii) aridity as function of MAT and AP; (iii) MAT as function of the AMO and the calendar years (climate warming); (iv) AP as function of the NAO, the MOI and the calendar years (reduced AP due to climate change); (v) the MOI as function of the NAO (see the initial SEM graphically in Fig. 3a). Since WeMOI and MOI are rather similar indices, we firstly analyzed SEM that included each index at a time to test which of both is more informative according to the Akaike Information Criterion corrected for small sample sizes (AICc). To account for the lack of independence of repeated measurements within individual trees in the growth model, we applied linear mixed models with a normal distribution of residuals to log-transformed BAI, in which tree identification was considered as a random effect. Importantly, and prior to SEM analyses, we sought for potential temporal autocorrelations in the BAI data by using an autoregressive correlation structure. To this end, a set of growth models were built using different orders of temporal autocorrelation (i.e., different number of autoregressive parameters), ranging from a non-autocorrelated structure to a fifth order temporal autocorrelation structure (Camarero et al., 2017). The AICc allowed selection of the best autocorrelation structure to be included in the SEM. Thereafter, we tested the three global change hypotheses by removing each corresponding arrow at a time from the full SEM and compared the resulting models with the full model using AICc similar as done it is done in a backward model selection procedure. We considered the inclusion in the final model of an arrow whenever its removal determines an increase in >4 units of AICc compared with the full SEM (Burnham and Anderson, 2003). Once the non-supported global change trends were eliminated from the initial SEM, we tested the goodness of fit using a chi-squared test on the Fisher's C statistic (Lefcheck, 2016). This test evaluates whether potential missing paths should be considered in the initial SEM. In other words, if the associated *p*-value is higher than 0.05, then a better SEM exists that incorporate paths not accounted for in our full SEM. Finally, we iteratively removed all non-significant missing paths and each time re-tested the model's adequacy.

Table 1
Hypotheses supporting inter-variable links in the full SEM. (All the literature cited in the 'References' Section).

Link No#	Hypothesis	Reference
1	Carbon fertilization	Keenan et al. (2011)
2	Climate warming	IPCC (2013)
3	Precipitation reductions	Del Río et al. (2005)
4	AMO influence on temperature	Steinman et al. (2015)
5	NAO influence on precipitation	Trigo et al. (2002)
6	MOI/WeMOI influence on precipitation	Conte et al. (1989), Martin-Vide and Lopez-Bustins (2006)
7	NAO influence on MOI	Tsimplis and Josey (2001)
8	Temperature contribution to aridity	UNEP (1992)
9	Precipitation contribution to aridity	UNEP (1992)
10	Temperature-growth relation	Bogino and Bravo (2008), Kurz-Besson et al. (2016)
11	Growth-aridity relationship	Sánchez-Salguero et al. (2010), Prieto-Recio et al. (2015)
12	DBH-BAI relationship in pine trees	Dănescu et al. (2017), Vilà-Cabrera et al. (2014)

The models' R^2 values derived from the variance of both fixed and random effects were calculated following Nakagawa and Schielzeth (2013). SEM analyses were realized in R using the *piecewiseSEM* package (Lefcheck, 2016). We used the function lme (package nlme) in R (Pinheiro et al., 2018) to fit Linear Mixed Models to BAI. In all the climatic regressions we applied generalized least squared regressions with an autoregressive structure of variance to account for first order temporal autocorrelation of data. We used the gls function (package *nlme*) in the R environment (Pinheiro et al., 2018).

3. Results

3.1. Tree-ring width chronologies at the tree level

Mean DBH among the sampled trees was 362.63 mm (±25.36 mm), and mean BAI was 26 mm^2, ranging from a minimum of 0.24 mm^2 to a maximum of 136 mm^2. Over the 50 years covered in this study, four rings show characteristic features among most tree individuals and can thus be considered as negative pointer years. Two of these four pointer years, 1992 and 2005, show very narrow rings common to all the trees sampled. Specifically in 2005, the narrow ring is representative of one of the most important droughts in the climatic records in the study area (see Fig. S1). The other two pointer years were narrow rings as well and reflect the impact of unusually cold (1984) and dry (1975) conditions on growth of 30 and 29 tree individuals, respectively. One of the 32 trees sampled was discarded at this step because it did not exhibit a consistent growth chronology when compared to the other individuals.

3.2. Effects of climatic and non-climatic components on BAI

Of the three hypothetical links between calendar years and MAT, AP, and BAI respectively, only the first one was supported by AICc (see Table S1). The best supported growth model included a third-order autocorrelation structure of error so we thereafter worked with this degree of temporal autocorrelation in the SEM (see Table S2).

The most important predictor in the growth model was the DBH in log form, followed by MAT and aridity (Fig. 3b). On the one hand, and as hypothesized, MAT had a two-fold effect on BAI: (i) a direct positive effect and, (ii) an indirect negative effect via increased aridity. On the other hand, AP drove BAI indirectly through its positive effects on the aridity index. The most important predictor variable of MAT was calendar years followed by the AMO (Fig. 3). Only the NAO had a significant effect on AP with a negative sign in the associated standardized coefficient. In this regard, and despite the fact that the AICc supported the MOI as the better predictor in the SEM as compared to WeMOI ($AICc_{MOI} = 170.591$, $AICc_{WeMOI} = 198.411$), the effects of both were negligible for AP even though a significant causal link between the NAO and the MOI was hypothesized. Thus, the NAO seemingly affects MOI but this direct effect does not translate into an additional indirect effect on AP.

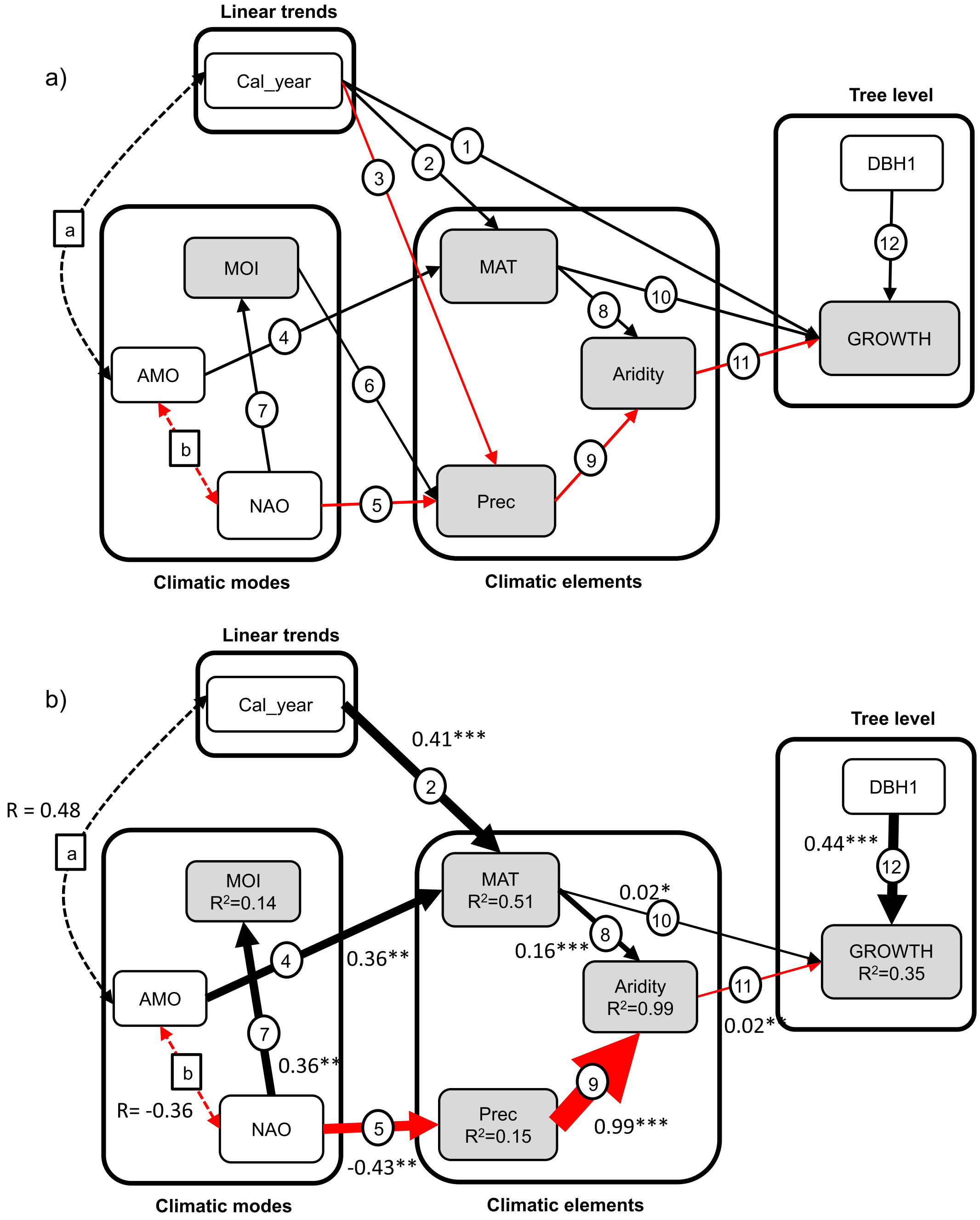

Fig. 3. (a) Initial SEM including all the hypotheses considered, and (b) best supported Structural Equation Model showing significant paths (p-values < 0.05) with the corresponding standardized parameters. Solid red arrows denote negative causal effects whereas solid black arrows do so for positive effects. Dashed arrows represent correlation with colours denoting negative and positive relationships. The thickness of arrows is proportional to the size of the standardized parameters. Conditional R^2 under endogenous variables are provided as a measure of goodness of fit. Legend for acronyms: Cal_years – calendar years; AMO – Atlantic Multidecadal Oscillation; NAO – North Atlantic Oscillation; MOI – Mediterranean Oscillation Index; MAT – Mean Annual Temperature; Prec – Annual Precipitation; Aridity – UNEP aridity index (Note that the BAI-aridity relationship is hypothesized to be positive because the UNEP aridity index is formulated as Prec/PET and thus increasing values represent lower aridity); Growth – yearly basal area increment. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Finally, and as expected, both AP and MAT affected aridity significantly with positive and negative influences, respectively.

4. Discussion

Our results support a significant, yet secondary, role of climate warming on tree growth relative to climatic variability associated to atmospheric/oceanic circulation (NAO and AMO, respectively) and tree size in this very extreme forest ecosystem. The climate warming trend represents one third of the whole climatic influence and, contrary to expectations, its direct positive effect on tree growth exceeded its indirect negative influence via aridity, at least over the last 50 years. Importantly, results did not support any significant trend attributable to either AP or carbon fertilization (i.e., direct link between climate change and BAI), and supported tree size as a primary determinant of tree growth.

4.1. Controls of endogenous factors

Our hierarchical approach allowed identification and evaluation of the influences of different sources of climatic variability while accounting for endogenous, ontogenetic factors such as tree size. In this regard, our results support a strong positive DBH-BAI relationship. In general, this relationship tends to hump-backed functional forms with maximum growth rates at 50–70 cm DBH (see Dănescu et al., 2017; Vilà-Cabrera et al., 2014). For larger DBH, BAI is assumed to decline due to reduced photosynthesis/respiration rates (Wyckoff and Clark, 2005). Physiological constraints underlying size tend to be critical in understanding growth dynamics along tree ontogeny but also tree mortality and growth decline under climatic extremes such as intense and frequent droughts (Carrer and Urbinati, 2004; Gomez-Aparicio et al., 2011; Madrigal-González and Zavala, 2014). Thus, size-driving effects on growth are also connected with environmental drivers and with competition through legacy effects (Ogle et al., 2015). In our analysis, we have disregarded biotic influences from surrounding trees given a low population density, with a high degree of spatial isolation of sampled individuals (neighbor trees at minimum distances of 10 m). Future studies should integrate, within a hierarchical framework, the role of neighbors as growth determinants as well as dependencies on other environmental factors such as precipitation or temperature (e.g., Sánchez-Salguero et al., 2015a).

4.2. Climatic controls and teleconnections

Our results are consistent with current findings that point to maximum temperatures coinciding with overheating of SSTs in extratropical latitudes of the northern hemisphere (AMO+ phases). Cooling periods of the Atlantic Ocean (AMO−), in turn, coincide with cold temperatures over the European continent, particularly in winter, as evidenced by the colder conditions during the 1950s–1980s (Steinman et al., 2015). The positive relationship between AMO and MAT, however, is insufficient to explain the abnormal rates of warming reached in the present years. Our model, as well as other contributions covering the 20th century in the Iberian Peninsula (Del Río et al., 2005; Brunet et al., 2006), support the existence of a linear warming trend independent of the atmospheric/oceanic circulation. This global warming is speculated to have net negative effects on tree growth and forest productivity in the Mediterranean through increased aridity and intense droughts (Lindner et al., 2010). However, in continental areas where winter temperatures are a limiting factor, warming has room for net positive effects (Sánchez-Salguero et al., 2015b). For instance, climate warming has been recently observed to promote opposing influences in Mediterranean forests at the dry limits of species distribution (Camarero et al., 2015; Marqués et al., 2018). On the one hand, (i) reduced growth rates can emerge in response to rising aridity via increased evapotranspiration and vapor pressure deficit (Will et al., 2013); on the other, (ii) rising MAT might be positive for growth through reduced impacts of cooling on photosynthesis (Medlyn et al., 2002; Galván et al., 2012) and freezing-induced embolism (Fernández-Pérez et al., 2018). The fact that this dry forest is placed in an inner Mediterranean area implies that winters are cold, with frequent nocturnal frosts (e.g. absolute minimum temperatures reach −12 °C) and mean maximum temperatures below 10 °C. Moreover, winter conditions in this area often expand until April, which in warmer winters may have favored an earlier activation of xylem differentiation and thus an extended growing period (Vieira et al., 2014). In similar climatic contexts, net positive temperature-growth relationships have been reported for this (Kurz-Besson et al., 2016; Sánchez-Salguero et al., 2018) and other pine species on the Iberian Peninsula (Sánchez-Salguero et al., 2015b; Andreu et al., 2007). However, our results also support secondary negative effects of warming through increased aridity which, in a scenario of linear warming, might lead to potential rank reversals due to prevailing negative impacts of rising aridity and increased drought frequency (Vicente-Serrano et al., 2011).

Our findings are also consistent with the general expectations posed on the NAO in this latitude (Trigo et al., 2002). This climate mode represents a latitudinal switch for oceanic influence in which the Azores High determines the direction of westerly winds towards the European continent, and consequently the precipitation regime. When strengthened (NAO+), the Azores High prevents the access of the westerlies to the Iberian Peninsula. This situation implies reduced advection of squalls and storms in the study region and simultaneously, increased diurnal temperature changes due to reduced cloud cover under stronger continental influence. As such, we observe a significant negative relationship between the NAO and AP. The NAO, therefore, affects BAI through indirect control of aridity via AP as might be expected under water limitations. Our study is thus in agreement with previous works in this (Prieto-Recio et al., 2015; Madrigal-González and Zavala, 2014) and other dry forest ecosystems (Sánchez-Salguero et al., 2010; Pasho et al., 2011) emphasizing the critical role of water in xeric habitats. Previous studies in this area point to a major role of seasonal precipitation on pine growth, mostly previous December and current spring precipitation (Bogino and Bravo, 2008; Sánchez-Salguero et al., 2018). Our findings, based on annual aridity from previous September to current August, agree with these conclusions. Besides, a recent study conducted in forest landscapes on the Iberian Peninsula gave substance to the critical role of winter water balance for forest productivity (Madrigal-González et al., 2017). Our outcomes are also in agreement with a study in a Mediterranean environment of North America for which Brooks et al. (2010) demonstrated how total precipitation during previous autumn-winter is critical for the recharge of the soil water fraction that is available for plants and thus, for subsequent growth (i.e. Camarero et al., 2013). Interestingly, we did not find any long-term trend in AP independent of the atmospheric circulation over the period covered in our study. Other previous studies in the Iberian Peninsula suggested that changes in seasonal patterns of rainfall might occur associated to climate warming. For instance, Del Río et al. (2005) found long-term trends of rising rainfall in summer along with significant reductions during winter and spring. Thus, a lack of long-term annual trends is not surprising whenever both trends are balanced.

4.3. Global change trends

Our results did not support a long-term signature attributable to carbon fertilization and increased water-use efficiency in the trees studied. Evidence of carbon fertilization at the landscape scale in this area has been recently provided using historical forest inventory data (Madrigal-González et al., 2015, 2017). This apparent disagreement gave support to the idea that benefits of carbon fertilization can be jeopardized under extreme climatic conditions that impose important growth limitations, and even lead to forest decay (Linares and Camarero, 2010). Similarly, Peñuelas et al. (2011) showed evidence in forests worldwide that increased water-use efficiency does not necessarily translate into proportional growth increments. Thus, increased water-use efficiency and carbon fertilization might occur in these forests without any signature in term of increased tree ring widths particularly in areas of high environmental harshness. Isotope analyses might help to elucidate whether carbon fertilization process is taking place without a clear signature on tree growth over the last decades (Shestakova et al., 2017).

4.4. Implications for forest management

Results reported in this study have important implications for forest management and resource exploitation in light of current and future climate change. The well-known oscillatory nature of both the NAO and the AMO might allow forest managers and practitioners to implement mitigation targets in anticipation of unfavorable periods of high drought risks. These adaptive measures oriented to adjust the forest structure and stocks to climate change scenarios, such as selective thinning, would help to increase forest resilience (i.e. Linares et al., 2010; Sánchez-Salguero et al., 2013; Vilà-Cabrera et al., 2018), especially in semi-arid ecosystems where drought-induced tree mortality can trigger cascading deterioration of valued forest services. However, several indications exist that might indeed jeopardize the effective implementation of such anticipatory adaptation measures in the coming decades. Firstly, ongoing climate change (IPCC, 2013) might eventually exceed the predominant role of natural climatic oscillations driving forest growth. Secondly, natural climatic oscillations could shift towards unprecedented modes of variability because of excessive and rapid climate warming. Indeed, reported findings in the North Atlantic region point to early signals of change (maybe even tipping points) in the atmospheric and oceanic circulations. Recent multidecadal variations of the NAO have been shown to alter climatic conditions through a modification of the ocean heat transport (i.e., in the North Atlantic overturning circulation), a rapid loss of Artic sea ice as well as changes in Atlantic tropical storm activity (Delworth et al., 2016). Previous studies in Central America raised major attention to changes in the Atlantic Meridional Overturning Circulation (AMOC) that might eventually change the energy exchanges between the ocean and the European continent (Bryden et al., 2005). More recent evidence confirms the slowdown of the Gulf current by up to 15% over the last decades (Caesar et al., 2018). Accordingly, an amplification of the AMO has been associated with the industrial-era warming since the mid- 19th century (Moore et al., 2017). In view of these changes, it is of paramount importance to improve our understanding on how climate change, along with natural sources of climatic variability, exert control on meteorological conditions and subsequently on tree growth (Camarero, 2011). This is particularly important in sensitive environments, such as dry forest ecosystems, which might act as "early warning systems" of climate change impacts worldwide (Camarero et al., 2015). In this context, it is essential to discern, in the short and mid-term, periods of high risk for forest productivity due to the coincidence of phases of key climatic modes associated with drought and other climate disturbances due to the global climate change. The two-fold effect of MAT also contributes to increase uncertainty in predictions posed on forest productivity under climate change scenarios. Other demographic variables such as mortality, nonetheless, should be accounted to properly address the question of how climate warming will affect forest at the edge under the potential paradox that growth and mortality (or even regeneration) do not necessarily go in parallel, and thus, increased growth rates due to climate warming might coincide with rising mortality during critical periods of water scarcity.

5. Conclusions

Our results establish a solid linkage between climate change and tree basal area increments in an extreme Mediterranean environment, which can be considered as representative of dry Mediterranean forests. Interestingly, climate change represent one third of climatic influences on tree growth and, until now, has had a net positive effect. However, this situation might change if one bears in mind that other climatic influences associated with global-scale patterns of climatic variability (such as the NAO and AMO), will drive aridity as well, and thus, also BAI. In fact, both the NAO and AMO, (closely tied to the AMOC), are likely to experience significant changes over the course of the 21st century evidenced already by the slowing trends of the Gulf current by up to 15%.

Climate-growth relationships obtained from tree-ring series have been classically evaluated with residual chronologies pooled at the level of populations. This approach, however, precluded the isolation of climatic effects from those mediated by individual, tree-level factors, such as competition, tree size or tree age. The methodological approach presented in this paper is, by contrast, based on SEM and intended to detect growth trends at the tree level (using basal area increments data). By doing so, we were able to build complex hypotheses employing direct and indirect linkages between global-scale processes and local growth factors, including endogenous drivers of growth (such as the ontogenetic development). This hierarchical procedure, nonetheless, assumes linear relationships among variables which – in the case of large environmental gradients – might be insufficient. Further efforts should be directed towards the development of suchlike hierarchical methodologies that are able to evaluate the relative contributions of linear and non-linear relationships among variables.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.06.064.

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