Irrigation in Mediterranean urban areas: a good strategy to face the ongoing climate change impacts on urban cedar trees?

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Abstract

Irrigated trees are known to develop large aboveground structures that can be detrimental during dry spells, and therefore irrigated trees are expected to perform worse than non-irrigated ones under climate change. In this study, we evaluated the climate-growth relationship of irrigated and non-irrigated trees of the species *Cedrus atlantica* (Endl.) Manetti ex Carrière (Atlas cedar) in an urban environment in central Spain. We first studied climate-growth relationships with and without irrigation to test the hypothesis that irrigated trees should be less sensitive to interannual climatic variability than non-irrigated ones. Secondly, we identified the four most intense droughts over the 21st century (2005, 2012, 2017, 2019) to test the hypothesis that growth resilience should be lower in irrigated than non-irrigated trees due to traits such as total height. Our results support the idea that irrigated trees are less responsive to climatic interannual variability and notably less resilient to drought stress, with these differences becoming more pronounced with age. These results suggest that irrigation may increase the risk in a

scenario of more frequent and intense droughts in Mediterranean urban areas. Thus, widening urban green areas to meet the European Green Deal 2030 in Mediterranean cities should consider better-adapted tree species and *ad hoc* adaptation to water shortage rather than watering and strategies based on resource supplements.

Key words: Urban greening, Atlas cedar, Mediterranean gardens, dendrhronology, resilience, resistance, growth sensitivity.

Introduction

The population of cities is projected to reach 9.7 billion people by 2050 (United Nations, 2018). Cities facilitate closer connections between individuals and offer multiple services, yet they also concentrate environmental problems (Barthelemy, 2019). Urban trees play a pivotal role in providing ecosystem services to society, such as mitigating warm temperatures, filtering air pollutants, reducing greenhouse gases through carbon storage, promoting the absorption of rainwater, or enhancing mental well-being, among others (Livesley et al., 2016). Nevertheless, they contend with a highly stressful environment compounded by extensive pavements, urban heat island, and climate change effects, that result in high tree mortality rates (Savi et al., 2015). Such increasing chronic stress negatively impacts urban trees, jeopardizing their function in cities and posing potential hazards in residents.

Rising drought stress and heatwaves directly contribute to increased mortality rates among people (Åström et al., 2015), highlighting the urgent need for governments to implement adaptative and mitigating strategies for climate change. Greening urban environments is one of the key strategies identified by the European Union (European Green Deal 2030) for climate change mitigation in the coming decades (Tutak et al., 2021). This greening strategy, however, will face significant challenges, especially in water-limited areas, where the establishment and growth of vegetation are strongly hindered by the harsh climatic conditions. In particular, the greening of cities in southern

Europe will face the difficult challenge of getting trees to grow and survive intense heat waves and increasingly intense and prolonged droughts (Madrigal-González et al., 2024).

Traditional gardening has strongly relied on plant irrigation in water-limited areas (Luketich et al., 2019). Since ancient times, plant species in urban areas and gardens have been selected using aesthetic criteria (Conway & Vander Vecht, 2015). From colours to growth forms, crown shape, leaf size, and canopy shape, annual plants, shrubs, and trees have been chosen to recreate exotic/magical spots. Gardens have, therefore, been conceived as artificial recreations of nature devoted to boosting emotions. However, water scarcity is anticipated in the future, potentially leading to a reduction in irrigation practices. In this scenario, hotter droughts, e.g. the combination of drought stress and high temperatures by the heat island effect (Oleson et al., 2011), could overpass their resilience capacity.

We lack knowledge about how species respond to hotter drought stress in novel environments beyond their natural habitats, particularly with contributing factors of tree decline such as pollution, intense pollarding, and poor soil conditions (e.g. soil compaction or tree pits). Irrigation reduces urban heat islands and promotes rapid growth and big structures (Fini & Brunetti, 2017) yet could also result in shallow root systems. While the strategy of irrigating generates fast-growing, large tracheids or vessels, high crown height, and cover, these trees could be less resistant and resilient to periods of water scarcity. Large canopies increase transpiration rates and larger cells increase the risk of cavitation and mortality (Savi et al., 2015). Understanding the mechanisms of drought resilience is paramount to promoting urban trees that provide all the ecosystem services while minimizing the need for anthropogenic irrigation. Quantifying the growth resilience in response to drought of urban trees dominated by multiple species with contrasting functional traits from different biomes all around the world is then a major research challenge.

This study aims to evaluate the drought resilience of urban trees in Cuéllar, a middle-size city of 10,000 inhabitants in central Spain, distinguishing between those subjects to irrigation and those left unirrigated. We focus on the Atlas cedar *Cedrus atlantica* (Endl.) Manetti ex Carrière (Atlas cedar), that is a highly popular choice for urban tree planting across the Mediterranean region. We first studied climate-growth relationships under and in the absence of watering to test whether irrigated trees are less responsive to interannual climatic variability than non-irrigated ones. Secondly, we identified the major recent warmest droughts to test whether growth resistance and resilience are lower in irrigated than non-irrigated trees. Our hypothesis posits that irrigated trees will exhibit greater growth, size, and height compared to their non-irrigated counterparts of the same age. Thus, we suspect that these oversized structures may lead to reduced resistance and resilience against the warmest drought impacts.

Materials and Methods

Study area

The study was conducted in the village of Cuéllar, Segovia province (Spain). This village is located in the northern plateau of the Iberian Peninsula (41.40º, -4.31º; 857 m asl). The climate is Mediterranean with high continental influence and strong interannual variability in temperature and precipitation. The mean annual temperature is currently 12ºC and total annual precipitation ranges 430-470 mm (2001-2023). The urban area extends > 2 km^2 by a moderate slope, oriented southwards.

The Atlas cedar (*Cedrus atlantica*)

Cedrus atlantica (Endl.) Manetti ex Carrière is currently distributed by north-western African mountain environments in the Rif, the Atlas, and the Aures (Morocco and Algeria) at altitudes ranging from 1300 to 2600 masl. However, humans have used this species in gardening and green urban species in North America, Europe, and Asia (mostly warm climates) and so it is currently one of the most widely distributed tree species in public and private owning urban areas. This species is well adapted to warming conditions and moderately to water scarcity.

Sampling and data recording

A total of 33 trees were identified in public and private properties scattered throughout the urban environment of the village. Total height (using a laser forestry hypsometer, Nikkon Pro II) and diameter at breast height (DBH, using tape measures) were measured for these individuals, and a tree core was collected at 1.3 m for dendrochronological analysis using a Pressler-type increment borer (Haglöf, Sweden). In addition, for each individual, its location was estimated through geographical coordinates using a GPS (Garmin eTrex Legend HCx), and the presence of irrigation systems was determined with the help of the municipal environmental technician. A total of 13 trees were discarded from further analysis due to a lack of precise information about irrigation since the time of planting. Thus, a total of 10 irrigated and 10 non-irrigated individuals were available for the study area.

Dendrochronological samples were transported to the lab for further preparation and analysis. We first glued samples onto wood sticks and then sanded using progressively thinner sandpapers until a proper identification of every growth ring. After that, all the samples were photographed using the CAPTURING system (García-Hidalgo et al., 2022), and tree ring widths were measured using the software CooRecorder (Maxwell & Larsson, 2021). We visually cross-dated all the samples using pointer years, which in this case corresponded to narrow rings associated with intense droughts in 2005, 2012, 2017, and 2019 respectively. Tree-ring width series were converted into basal area increment (BAI; Biondi & Qaedan, 2008) Tree age was estimated by counting the total number of tree rings when the sample contains the pith of the trunk. Alternatively, the CooRecorder target device was used to calculate the potential number of rings lost in case the sample does not reach the pith.

Climatic data on monthly precipitation and temperature were retrieved from a nearby climatological station placed in the village of Gomezserracín (41.29°, -4.32°; 803 m asl; 11 km far from the study area). We used this climatological data because of the lack of a long enough record available in Cuéllar (2009-2024). Otherwise, the altitudinal differences are minimal (-54 m asl), and the terrain in between is flat and homogeneous, so it is possible to assume the validity of this climatic information. Following the results of the sample depth of the chronologies with and without irrigation (Appendix 1, Fig. S1), we considered 1998-2021 as the appropriate time window for the subsequent analyses. By selecting this period, we avoided the first years of each tree to reduce the effect of planting trees of a certain age from greenhouse. We used the index Precipitation / Potential Evapotranspiration (September of the previous year to August of the current year) as a metric of aridity which is commonly used in ecological studies. Potential Evapotranspiration (PET) was assessed using the Thornthwaite index (Thornthwaite, 1948). It is worth noting that the larger the values of the aridity index the lower the aridity conditions.

We selected the driest years in the record based on precipitation-to-potential evapotranspiration (PET) data from a long-term meteorological station located in the city of Segovia, 64 km from the study area. The station's meteorological data spans from 1920 to the present (see Appendix 1, Fig. S1). Using a statistical criterion based on the 10th percentile, we established a threshold of 0.598 (precipitation/PET), below which values indicate particularly dry years. According to this criterion, the years 2005, 2012, 2017, and 2019 are identified as extreme dry years (Fig. 1).

Statistical analyses

We first evaluated the hypothesis that irrigated trees are less responsive to climatic variability, particularly aridity (sept-aug aridity), by fitting linear mixed models to BAI at the individual tree level. We evaluated BAI as a linear function of the interaction between the aridity index and irrigation (Watered/Not watered) plus tree age in second-order polynomial form. We included ‘tree individual’ as a random factor and considered a first-order autoregressive model to account for potential temporal autocorrelation among the annual BAI measurements. We used a backward selection of the fixed effects by subtracting each term at a time. We evaluated the contribution of each fixed term using the Akaike Information Criterion corrected for small-sized samples (Hurvich & Tsai, 1989) through delta AICc (ΔAICc) as follows:

$$\Delta AICc = AICc_{full\ model} - AICc_{model\ i}.$$

Where ΔAICc is the delta AICc, $AICc_{full\ model}$ is the AICc of the full model and $AICc_{model\ I}$ is the AICc of each model i obtained by removing any given fixed term. We considered a fixed term to be included in the final model when its elimination from the full model implies a ΔAICc equal to or lower than -4 units (Burnham & Anderson, 2004).

Second, we used linear mixed models to examine potential differences in drought resilience between irrigated and non-irrigated trees. To do so, we calculated relative resilience and resistance indices following Lloret et al. (2011) from annual basal area increments (BAI), and considering the four driest years during the 21st century (i.e. 2005, 2012, 2017, and 2019, Fig. 1 and Fig. S2). We used a one-year window to compute the indices in order to avoid overlap, as two of the four dry years (i.e., 2017 and 2019) are separated by only one year. In both cases, resilience and resistance were evaluated as a linear function of the interaction ‘irrigation (Watered/Not watered) x tree age (second-order polynomial)’ under the assumption that differences in resilience and resistance after drought will become gradually more evident as tree size increases. We considered individual trees as a random factor in the model. Model selection was conducted using a similar procedure as in previous models (backward selection using AICc). We used the function *lme* of package nlme in the R environment (Pinheiro et al., 2018)

Finally, we evaluated the influence of irrigation on tree size fitting linear models (ANOVA) on tree DBH and Height both made relative to age. To this end, we used the function *lm* in the R environment.

Results.

All the trees studied were relatively young, with an average age of 37 (± 1.77) years old, being irrigated trees slightly younger than non-irrigated trees (Table 1). Regarding size, the mean DBH was 36.5 cm (±2.67), with differences between irrigated and non-irrigated trees lower than 2 cm on average. On the contrary, irrigated trees showed considerably greater heights than non-irrigated trees (Table 1). In general, the health status of the trees was good, with no apparent damage caused by physical impacts, potential pathogens or herbivores.

A preliminary view of basal area increments (BAI) data suggested higher annual growth rates in irrigated than non-irrigated trees throughout the time window considered (Figure 1). Interestingly, both irrigated and non-irrigated trees showed notable negative responses to the main dry years of the period (i.e., 2005, 2017, 2019), with the exception of 2012, when no negative response in the averaged BAI was detected. Accordingly, model results confirmed these observations. Specifically, irrigation and climatic aridity both positively affected tree growth, but their interaction had a negative effect, indicating that climatic aridity had a more pronounced effect on non-irrigated trees (Table 2 and Figure 2). Fixed effects selection also supported a quadratic relationship between BAI and tree age (Figure 2).

Fixed effects selection applied to the relative resilience model supported the interaction between tree age and irrigation (Table 3). Thus, differences in relative resilience between irrigated and non-irrigated trees were almost inexistent in individuales younger than 20 years but became more conspicuous with aging, being non-irrigated trees the most resilient to the driest years under study (Figure 3). On the contrary, model results did not support differences in resistance to drought between irrigated and non-irrigated trees (Table 3).

Finally, linear models supported irrigated trees to be significantly larger in height ($Height_{irrigated}$ = 14.32 m ± 0.85, $Height_{non\text{-}irrigated}$ = 10.79 m ± 0.90), but not DBH ($DBH_{irrigated}$ = 37.34 cm ± 4.24, $DBH_{non\text{-}irrigated}$ = 35.67 cm ± 3.45; Figure 4).

Discussion.

Irrigated trees of the species *C. atlantica* in urban areas are less sensitive to interannual variability in aridity and, in parallel, less resilient to drought than their non-irrigated counterparts. This idea connects with the necessity to develop a specific agenda to deal with the urban green deal of the European Commission in the Mediterranean. Besides, this result relies on the paradox of greening in seasonally dry environments. In this environments, growing large green canopies implies the investment of scarce resources at the cost of emergent vulnerabilities associated to higher probability of hydraulic failures and embolism (Madrigal González et al., 2024).

Some authors have shown that water availability is crucial for the growth of conifers, primarily influencing cambial activity and xylogenesis (Vaganov et al., 2006). In the case of Atlas cedar, sensitivity to precipitation variability is most strongly linked to winter precipitation patterns in the Mediterranean, which are essential for soil water recharge and subsequent availability during the summer months (Navarro-Cerrillo et al., 2019; Linares et al., 2013). Recent research supports the notion that precipitation is vital for Atlas cedar growth, revealing significantly higher sensitivities to precipitation at the driest sites along a latitudinal gradient from southern France to southern Spain (Camarero et al., 2021). Additionally, notable declines in growth due to increasing aridity have been observed in Atlas cedar populations in northwestern Africa since the 1980s (Slimani et al., 2014; Navarro-Cerrillo et al., 2019). Similar negative growth responses to rising aridity have also been documented in other cedar species throughout the southern Mediterranean Basin (Linares et al., 2013; Bhattacharyya et al., 2023).

In urban environments, the extensive use of pavement increases surface runoff and significantly reduces the infiltration of precipitation into the soil, worsening aridity, particularly for trees that do not receive irrigation (Savi et al., 2015). However, irrigation can help alleviate these effects by promoting relatively stable tree growth during the dry summer months (June–September), thereby decreasing sensitivity to fluctuations in precipitation. It is important to note that trees in urban environments are typically young, especially when considering the long lifespan of this species in natural settings. This youthfulness may limit their long-term growth potential (Slimani et al., 2014; Esper et al., 2007). Previous studies have shown that growth sensitivity to precipitation variability in Atlas cedar is age-dependent, with younger trees being more sensitive than older ones under natural conditions (Linares et al., 2013; Dhyani et al., 2022). Given this, we anticipate that urban trees—particularly those in non-irrigated areas—will remain highly sensitive to aridity, especially if younger trees continue to dominate in urban settings.

Irrigation can be restricted during intense and prolonged droughts such as those highlighted here, according to the necessity to save water for human priorities (i.e. water for human consumption). Unexpectedly, growth resistance did not show significant differences between irrigated and non-irrigated trees. This means that irrigated trees, even if they are less sensitive to the temporal variability of climatic aridity, experience similar growth reductions when compared to their non-irrigated counterparts during intense dry spells. Importantly, irrigation did not influence the stem radial size of trees but stem height: i.e. irrigated trees had significantly taller stems than non-irrigated trees. This result is in line with current knowledge that, as trees grow in height, gravity and path length resistance limit height development through restrictions on leaf expansion and photosynthesis (Koch et al., 2004). Accordingly, tree height will increase as it increases the soil water availability to sustain leaf expansion and photosynthesis at the cost of a growing vulnerability to extreme events such as dry pulses due to comparatively wider water transport conduits that are exposed to higher conduct-blocking embolism risk (Olson et al., 2018). While some literature supports that taller trees can be comparatively less resistant to drought (Camarero et al., 2024), recent global results suggest that drought-induced stress in gimnosperms is related to changes in recovery (resilience), while resistance remains similar (DeSoto et al., 2020).

Our results on growth resilience to the intense dry spells of 2005, 2012, 2017, and 2019 pointed to an age-dependency in the sense that differences in resilience between irrigated and non-irrigated trees became more patent with tree age. Interestingly, and according to our second hypothesis, irrigated trees were less resilient, particularly the oldest specimens. This age-dependency of resilience between irrigated and non-irrigated trees suggests that resilience capacity is concomitant with tree-level characteristics tied to age such as stem height. Recently, Camarero et al., (2024) reported a significant negative relationship between tree height and xylem resistance to cavitation after post-drought growth recovery in conifers subjected to seasonally dry conditions. Evidence in North American forests also supports this notion that taller trees are more prone to die off after intense drought events (Stovall et al., 2019). Even if extreme drought pulses don't lead to sudden mortality directly, they can trigger dieback in trees which can previously manifest as significantly lower recovery, particularly in gymnosperms (DeSoto et al., 2020). This age-dependency of resilience should, nonetheless, be inferred with caution in our case study since tree age goes in parallel with potential confounding factors. For instance, several consecutive dry spells over the last two decades of the 21st century have occurred that could be lowering resilience progressively as a consequence of accumulated negative impacts, and this could be particularly patent in the most vulnerable trees (tallest trees). Evidence in this line has been provided for three pine species in the northeast Iberian Peninsula where findings supported a growing vulnerability to drought after consecutive dry spells over the last half century (1951-2010; Serra-Maluquer et al., 2018).

Our results suggest that supplying water to urban trees in Mediterranean climate environments may lead to medium- to long-term issues in relation to their persistence in a scenario of more intense and prolonged droughts. In the worst-case scenario, with a complete cessation of water inputs to irrigated trees, the consequences could be significant, leading to massive tree dieback. However, water supply seems to be decisive for increasing canopy cover and thus the mitigating role of heat islands in cities and other ecosystem services. For this reason, the greening of urban environments as a strategy to cope with climate change requires careful risk assessment in water-limited environments where water supply artificially depletes water reserves for human consumption while increasing the vulnerability of vegetation, in this case trees, to the negative impacts of climate change. While the use of drought-adapted species is essential the design of green canopies for the coming decades, it will be also important to carefully allocate scarce resources toward developing these canopies. This approach will help maximize resource efficiency while minimizing the risk of dieback in the medium term. Even though the case study of this study comprishes a local environment and a limiting number of tree specimens, its pseudo-experimental design provides insightful evidence on the complex paradox around the needs for water and the risk for its usage in places such as the Mediterranean, which are forecasted a hotspot of climate change impacts for the turn of the present century. A small sample size of trees may make it difficult to identify clear patterns, particularly when there is high variability between individuals. In this context, the observed lack of patterns in resistance could suggest that the variability between trees is considerable, and therefore, a larger sample size would be necessary to draw reliable general conclusions to this regard. However, we believe that the tree-level approach used in this study, despite the limited number of individuals, is the most appropriate. Furthermore, detailed knowledge of the irrigation history at the individual tree level is often scarce in urban environments, especially when focusing on specific species. Cities typically host a diverse range of species with varied origins and characteristics, and tree replacement is common in urban gardening practices to refresh vegetation and accommodate changing aesthetic trends.

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Tables.

Table1. Descriptive statistics for watered and not watered trees over the time period 1998-2021.

	Watered	Not Watered
Tree age (yrs)	35.8 (± 3.37)	37.9 (± 1.28)
DBH (cm)	37.34 (± 4.24)	35.67 (± 3.45)
Height (m)	14.32 (± 0.90)	10.79 (± 0.85)
Mean BAI (cm^2)	210.74 (± 11.9)	125.66 (± 7.8)
N	10	10

Table 2. Results of the backward selection of the fixed-effects term in the growth model using the Akaike Information Criterion corrected for small sample size (AICc).

Fixed effects	**AICc**	**Delta_AICc**	**Supported**	**R-squared**
Null model	737.1			
Full model (Irrigation x Aridity) + Age (2nd order polynomial)	698.7		*	0.25
Full model - interaction Irrigation + Aridity + Age (2nd order polynomial)	705.6	6.9		

Full model – Age (Irrigation x Aridity)	713.7	15		

Table 3. Results of the backward selection of the fixed-effects term in the resistance and relative resilience models using the Akaike Information Criterion corrected for small sample size (AICc).

Model	**Fixed effects**	**AICc**	**Delta_AICc**	**Supported**	**R-squared**
Resistance	*Null model*	84.4		*	-
	Full model (Irrigation x Age (2nd order polynomial))	89.0			
	Full model - interaction Irrigation + Age (2nd order polynomial)	89.6	0.6		
Resilience	*Null model*	104.6			
	Full model (Irrigation x Age (2nd order polynomial))	84.8		*	0.38
	Full model - interaction Irrigation + Age (2nd order polynomial)	100.4	5.6		

Figures.

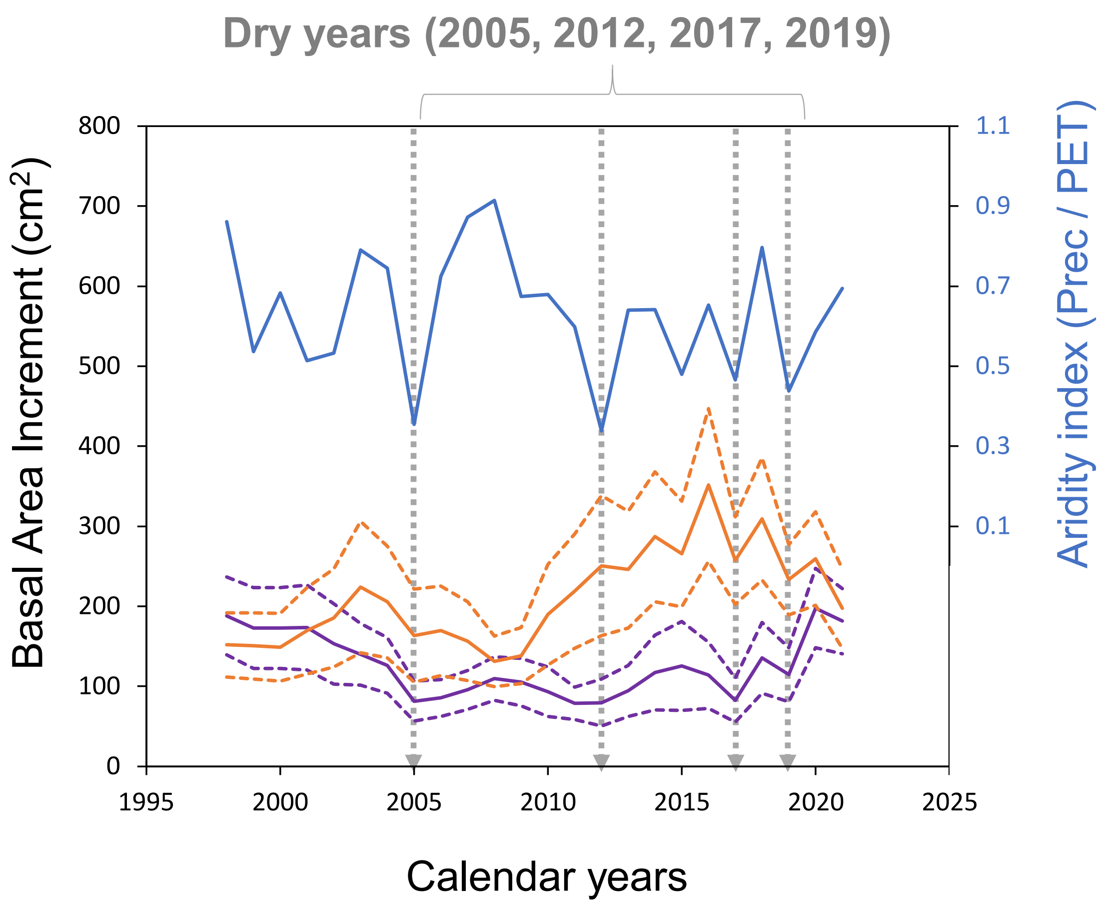

Figure 1. Composite plot for mean annual basal area increments of irrigated (orange solid line ± SE in dotted lines) and non-irrigated (purple solid line ± SE in dotted lines) Atlas cedar trees next to values of the aridity index (Precipitation / Potential Evapotranspiration) (blue solid line). The four driest years of the 21st century are indicated with vertical dotted red lines.

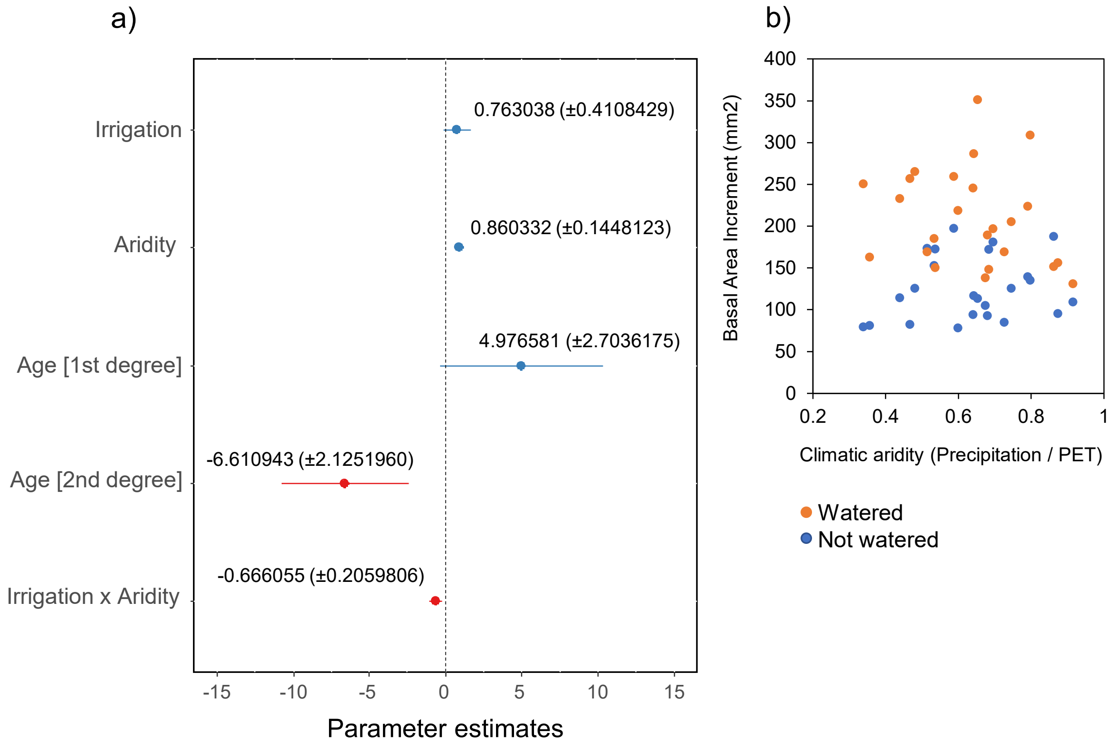

Figure 2. Graphical representation of the fitted mixed-model to growth metrics (Basal Area Index, BAI). a) Parameter estimates diagram for the best supported growth model in which the BAI (Basal Area Increment) is expressed as function of tree age in 2nd order polynomial and the interaction between irrigation (yes / no) and aridity (Prec / PET). In brachets, standard error associated with parameter estimates. b) Scatter plot of mean annual BAI metrics as function of climatic aridity (precipitation / PET) coloured by watered (orange points) and not watered (blue points) treatments.

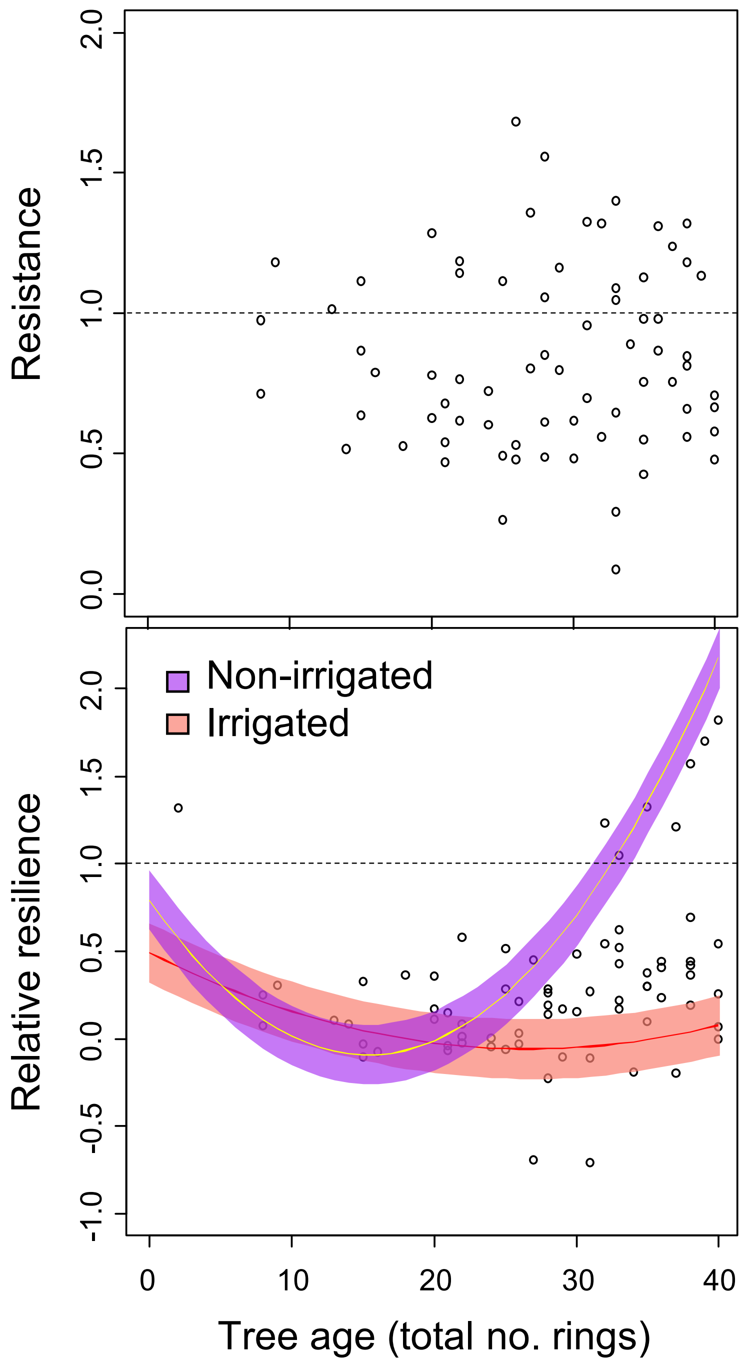

Figure 3. Resistance (a) and resilience (b) of tree growth in response to the interaction of tree age and irrigation considering the driest years of the studied period (2005, 2012,

2017, 2019). While model selection using AICc did not supported the influence of irrigation on resistance, it did so for the influence of age x irrigation interaction on resilience. Model predictions for irrigated and non-irrigated trees are shown in orange and pruple colours respectively.

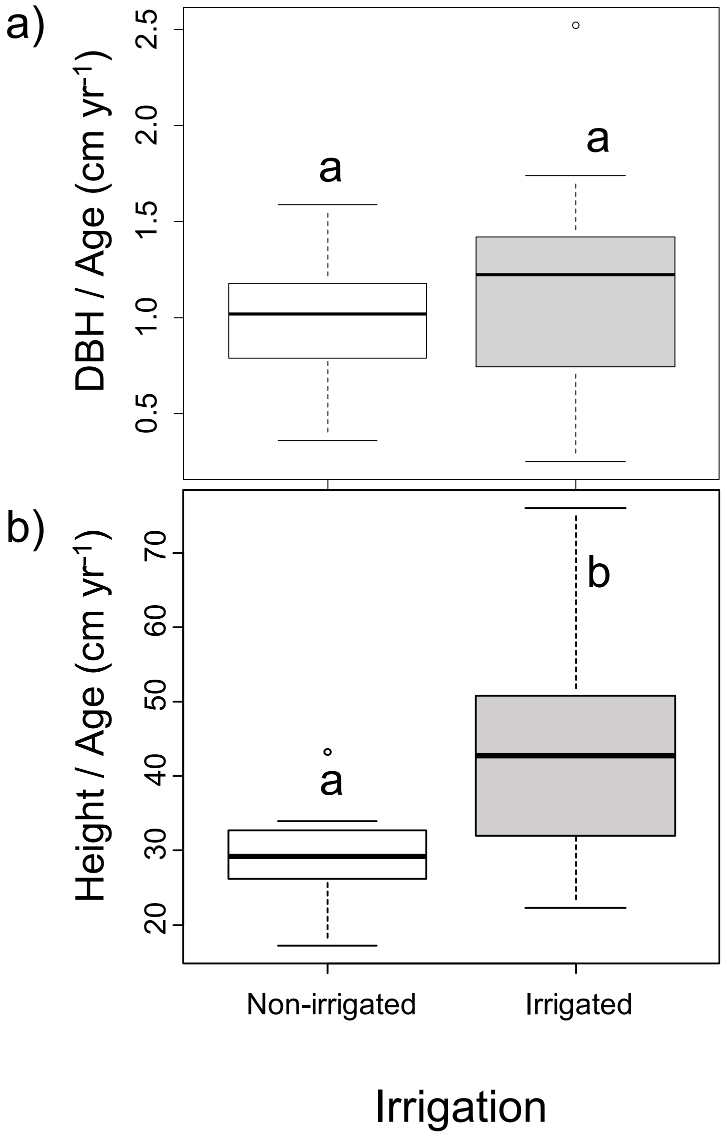

Figure 4. Size relative to age as function of irrigation: a) radial size, b) height. Different letter denotes significant differences in size driven by irrigation treatment.