Climate factors and oak decline based on tree-ring analysis. A case study of peri-urban forest in the Mediterranean area.

Short title: Oak decline and dendroclimatological analysis

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The main objective of this research was to investigate climate-growth relationships and if climate is a possible cause of oak decline in a very representative peri-urban forest in the Mediterranean area. The dendrochronological behaviours of healthy trees and declining trees were compared according to compromised vitality as assessed by crown defoliation. The analysed parameters were ring and latewood widths. The results showed that ring widths and latewood depended directly on spring precipitation (April-May-June) and, inversely, on spring-summer temperature (April-May-June-July). The growth histories of healthy and declining deciduous oaks in Castelporziano, as evaluated by their crown vitality, were very similar. The onset of decline dates back to the middle of the 1940s, and a further irreversible growth depression was based on the increase in temperature in the 1980s. This climatic change is reflected roughly 13 years later in declining trees, 17 years later in the healthy ones, in a strong growth depression that appears very exacerbated by the recurrent warm extreme events after the 2000s. Latewood in our study did not add more to the total ring-width measurements, potentially because of a high state of tree suffering. Declining trees were in general older than healthy ones, but in this study, the difference in age was not different from a statistical point of view.

1 Introduction

Deciduous oaks can be considered one of the most important groups of species of the genus *Quercus*. They characterise the landscape of the Mediterranean area both in forests and in urban and peri-urban woods. Currently, their health and survival are seriously at risk because oak decline has increased over the last two decades and mortality has been documented in forests worldwide (Allen et al. 2010; Ibáñez et al. 2016; Gentilesca et al. 2017). Forest decline and mortality have been ascribed more frequently to various causal factors that result from the interaction of predisposing (e.g., low site productivity, advanced tree ages), inciting (e.g., climatic changes, insect defoliation, droughts) and contributing factors (e.g., poor forest management practices, bark beetles) (Manion 1991).

Generally, the symptom of oak decline that alerts foresters and society as being predictive of mortality is the abundance of crown defoliation that is also represented by dead branches (Drobyshev et al. 2007a; Tulik 2014; Čater 2015; Tulik and Bijak 2016). However, crown vitality is not always necessarily an indicator of an irreversible decline of the tree. Another indicator which shows significant promise in this respect is tree-ring width. Comparison of tree-ring series according to variations in the severity of symptoms of crown defoliation and the to-date pattern of radial growth that precedes tree mortality can be particularly useful (Lombardi et al. 2008; Cailleret et al. 2016). Furthermore, tree-ring analysis detected climatic change as one of the most important drivers of forest decline (Di Filippo et al. 2010; Andersson et al. 2011). One important contribution, which can act in a complementary manner with dendrochronology, is the use of aerial photographs in a GIS environment. With a diachronic approach, the latter can help reconstruct the ecological dynamics of the landscape and changes in canopy cover. Studies on oak decline using tree-ring analysis in the Mediterranean area have been performed mainly on forest coppice stands (Corona et al. 1995; Amorini et al. 1996; Di Filippo et al. 2010) and it is necessary to enlarge the case studies to high volumes of forest seriously threatened. Climate change is rapid and extreme in the Mediterranean basin and its deleterious effects are even more abrupt in urban areas (Ordóñez and Duinker 2014). Urban forests are crucial as they have a “pillow” function by providing a multitude of ecosystem services (Manes et al. 2012). Therefore, when there is a phenomenon of dieback, as in Castelporziano, it is necessary to understand the cause of decline and any possible solution to enhance the resilience of the ecosystem.

With these assumptions in mind, the work presented here seeks to investigate the declining status of monumental oaks in a very representative peri-urban forest of the Mediterranean area, specifically the estate of Castelporziano located approximately 20 km from the Metropolitan area of Rome. The estate of Castelporziano is a true hotspot of biodiversity and, owing to it being an ecosystem at very high risk, its conservation is a priority.

The specific aims of this investigation were:

1. To establish climate-growth relationships and assess whether climate is a possible cause of oak decline; and
2. To compare the dendrochronological behaviours of healthy trees and declining trees according to compromised vitality as determined by crown defoliation and dead branches.

2 Materials and methods

2.1 Study area

The Presidential Estate of Castelporziano (41°41'54,56" N; 12°21'9,50" E) covers an area of roughly 6000 ha. It is well-known internationally because it is the summer residence of the President of the Republic; therefore, it is highly protected and included in the Natura 2000 network.

The soils are primarily made up of stabilised old sand dunes and contain a free water table with the presence of a superficial groundwater table in most of the investigated land. The area has been inhabited for a very long time with evidence of strong activity dating back to Roman times and even before. Anthropogenic activity lasting for such a long time has deeply modified the landscape of the area. At present, the site is burdened with very strong urbanization with about 200 inhabitants per square kilometre, and it is jeopardised by elevated anthropogenic pressures which have greatly accelerated the degradation processes (Trotta et al. 2015).

From a climatic point of view, the site is classified as Mediterranean, referring to the climatic data of Rome – Collegio Romano, with a hot and dry period between May and September (Figure 1).The mean annual total precipitation in Rome (1862-2013) is 711 mm, while the mean annual temperature is 16.1°C.

Figure 1 Study area and meteorological data. *Left*: Local overview of sampling areas within the Presidential Estate of Castelporziano (*red contour on colour orthophoto*). *Right*: Bagnouls-Gaussen's diagram for the period 1862-2013 deriving from the data of the meteorological station of Collegio Romano (Rome). The sum of monthly precipitation (mm) and mean monthly temperatures (°C) are reported.

The landscape represents a typical Mediterranean forest ecosystem along the Tyrrhenian coast with relicts of mixed deciduous and evergreen woods, Mediterranean shrubland, xeric vegetation of pastures, wetlands, and dunes. The most represented vegetative type is the mixed deciduous oak species. The oak high forest can be classified as mature, and over the last 50 years, it has not been subjected to any more silvicultural treatment.

2.2 Sampling and tree-ring measurement

The samples for dendrochronological analysis were collected in the spring of 2014.

In total, 38 trees were sampled with a diameter at breast height (DBH) spanning from 27 cm up to 103 cm and an age range between 52 to 215 years in different zones of the estate. It was allowed to collect no more than one core for each tree.

Core sampling was performed on selected healthy trees and on the declining ones according to their crown defoliation. It was decided to assess decline status in the tree only when there was an estimation of at least 20% of defoliation in the crown using the same criterion adopted by Tulik (2014) (Figure 2). The sampled trees belong to deciduous species, such as English oak (*Q. robur* L.) and Turkey oak (*Q. cerris* L.), but also downy oak (*Q. pubescens* Willd.) and Italian oak (*Q. frainetto* Ten.). Some of the sampled trees did not demonstrate discretely clear species characteristics, so they may be regarded as hybrids. The main characters of age and DBH are reported in Table 1, dividing the subgenus', *Quercus Oersted* (Q. *robur* L.) and *Cerris* (Spach) Oersted (Q. *cerris* L.), according to Schweingruber (1990).

Table 1. Number of trees classified according to vigour classes. Minimum (Min), maximum (Max), and mean value (MV) with standard deviation (SD), respectively, of diameter at breast height (DBH) and age were reported of the 26 cores suitable to be included in the mean curves
Diameter at Breast Height and Age of the investigated trees classified according to the vigour class.

Figure 2 Four oaks representing different vigour classes: (a) healthy, (b) declining, (c) standing dead, and (d) fallen dead trees.

Ring-width (RW) series and latewood (LW) width series were measured at 1/100 of mm by the LINTAB system (Rinn Tec) and classical dendrochronological analysis was carried out (Romagnoli and Codipietro, 1996; Corona et al., 1995).

It was decided to work with two mean curve representatives of the Castelporziano site (healthy and declining) because it was not permissible to sample a higher number of trees that could be used to build a mean chronology representing ecological behaviour at the species level and because of a very robust inter-tree synchronization. Among the 38 sampled trees only 26 were included in the mean curves due to broken cores or to a very poor inter-synchronization

The boundary between earlywood and LW was established at the end of the vessels in the porous zone of the ring, which in some cores was represented by one-two rows of vessels while in other samples, extended up to the third row of vessels. It was decided to not take into account earlywood in the following analysis because earlywood chronological series were not so well synchronized to each other. The most important dendrochronological parameters, i.e., mean value, standard deviation, coefficient of variation, and mean sensitivity, were calculated based on the raw values of RW and LW in healthy and declining trees. In order to verify the relationships with climatic parameters, mean inter-correlation and EPS were also elaborated. Using Kruskal-Wallis test (statistical programs: R package, version 4.0), a possible statistical difference among diameter, age, dendrochronological parameters between healthy and declining trees was investigated. Pointer years were detected according to Schweingruber et al. (1990) looking at least 70% of the trees showing the same trend in growth.

2.3 Dendroclimatological analysis

For the dendroclimatological analysis, according to the common length of the 26 tree-ring series, the period considered was from 1925 to 2013.

A matrix of 24 regressors comprising monthly precipitation and maximum mean temperature (PTMAX) along with monthly precipitation and minimum mean temperature (PTMIN) was arranged starting from the climatic parameter of October of the previous year of growth (t-1) to September of the current year (t) (Romagnoli and Codipietro 1996). Both raw RW and LW time series were detrended using a spline model with a time lag of 11 years via PAST software (SCIEM, 2000), and later, in order to enhance the high frequency signal, the first-order autocorrelation was removed by applying the auto-regressive moving-average model (ARMA; 1.0).

The response functions were estimated by means of the bootstrap method processed on mean chronology of the residuals (detrended and then transformed by ARMA) (Romagnoli and Codipietro 1996; Helama et al. 2009; Di Filippo et al. 2010). The bootstrap method considers the calibration and verification period for the calculation of the regression coefficient. In the present study, dendroclimatic analysis was computed via 3Pbase software (Tessier et al. 1994; Guiot and Goeury 1996). The response function profile was expressed by codes of the monthly partial regression coefficients and their standard deviations. The preliminary analysis was performed on 24 regressors, and then the climatic parameters were merged in order to improve the statistical significance of response functions by reducing the number of regressors. The union was based on their signal (positive or negative) and their importance in determining growth. Precipitation of October-November-December of the year t-1 was summed as April-May-June while the average of the minimum and maximum monthly temperatures of the months April-May-June and July were calculated. Response functions calculated were run again with the elaborated 17 regressors (sum of precipitation: October to December, January, February, March, April-June, July, August, September; temperature: October, November, December, January, February, March; mean temperature: April-July, August, September). This procedure was employed several more times to calculate the response functions of oak (Romagnoli and Codipietro 1996; Corona et al. 1995; Nola 1991; Tessier et al. 1994) in order to highlight the most significant signals with the same trend (positive or negative) of response to the climatic parameters. The months showing a little significant signal and an opposite trend, compared to the near months, were not merged with the others.

In order to detect the possible climatic triggering factor of high and medium frequency, the departures from the mean of the most important climatic limiting factor, resulting from the response function analysis, were superimposed on to the mean dendrochronological curves. Furthermore, a trend curve of a moving average of five years was fitted on climatic data and on the standardized ring widths (Romagnoli and Codipietro 1996; Di Filippo et al. 2010). Extreme years were identified in the period 1925-2013 according to the most limiting climatic factors for growth. The values of the total precipitation lower than the 10th percentile in the months April, May, and June were considered extreme events impacting growth negatively, as were values higher than the 90th percentile of the minimum temperature of April, May, June, and July (Table 3) (Rammig et al. 2015). Raw RWs lower than the 10th percentile were considered to be affected by extreme events. On the contrary, mean temperatures lower than the 10th percentile and precipitation higher than the 90th percentile were compared with RW widths higher than the 90th percentile in order to investigate the effect of positive extreme events on tree-ring growth (Rammig et al. 2015).

Piecewise linear regression with the breakpoint determined by the Quasi-Newton method (Darlington 1990) was used to determine the slope of trend growth among different periods in healthy and declining series. The results were compared with the breakpoint seen in the most significant climatic parameter affecting tree-ring growth, i.e., the average of minimum temperature of April, May, June, and July in the period, 1925-2013.

2.4 Aerial photographs

To evaluate land cover changes, we first scanned and geo-referenced four scenarios (1945, 1959, 1980, 2000) of high-resolution vertical aerial photographs that encompassed a 54-year time period from the end of 1940 to recent times (2000) and covered the same geographic area. The historical photographs had a scale of 1:27,000 and were scanned at a resolution of 400 dots per inch, while the recent photographs had a scale of 1:12,000 and were scanned at a resolution of 200 dots per inch; this led to similar grain sizes of 1.7 and 1.5 m, respectively, for the two photograph sets. We systematically sampled, registered, and rectified all photograph images using existing streams and road coverages in ARCGIS (Environmental Systems Research Institute, 1998). The accuracy of registration was measured with the root mean squared error (RMS error) for the image, and the distance between calculated x, y, and true x, y coordinates for each link (Environmental Systems Research Institute, 1998). Images were reregistered (links added and dropped iteratively) until the following two criteria were met: any single link on an image could not have an RMS error greater than 30 m and the mean RMS error for the entire image could not exceed 25 m. 27 links per photo were utilised to join the photo and GIS coverage locations. RMS errors for individual links customarily fell within the 3–20 m range but were typically less than 10 m. After the dendroclimatological analysis was carried out, a further verification of the aerial photograph of the most representative periods of tree decline and climatic stress was conducted. Three scenarios were photo interpreted where dead trees were located based on very high magnification.

3 Results

3.1 Dendrochronological parameters

Tree-ring dating showed that the oldest tree was at least 215 years old because the sample core was almost reaching the pith. This belonged to the Turkey oak species that exhibited crown defoliation and many dead branches. However, symptoms of decline as defined by crown conditions were also detected in younger trees.

Through raw RW curves (Figure 3a) and bar diagrams, it can be seen that the trees classified as declining are usually older than those that are healthy and the corresponding curve is below the curve of healthy trees up to middle of 1940. Figure 3b depicts the indexed values of healthy and declining curves of RW and LW, the graphs of the indexed ring values overlap.

Descriptive statistics of the dendrochronological parameters (Table 2) of raw RW feature a number of interesting differences among healthy and declining trees. The MV in RW indicates how declining trees have, in general, a lower RW value than healthy trees; sometimes, this is because of the presence of older trees. Declining trees are more sensitive compared to healthy ones

Table 2 Statistical parameters of mean tree ring width (RW) and mean latewood (LW) width for healthy and declining trees: Mean value (MV), standard deviation (SD), coefficient of variation (CV), mean sensitivity (MS), mean correlation between trees, and expressed population signal (EPS).[a] EPS was calculated considering the common period of 1963-2014 (52-year interval)

Figure 3 Comparison of mean total ring width (RW; mm) and mean latewood (LW; mm) of healthy (solid blue line) and declining (dotted-red line) trees at the Castelporziano site: column (a) raw data; column; (b) indexed data; and (c) number of replications both for healthy and declining trees at the site of the Castelporziano Estate for each year**.**

Similarly, LW was lower for declining trees versus healthy ones (Table 2). RW and LW exhibited a large variability in their high standard deviation values and in their high coefficients of variation, even if the higher values were detected in LW. Mean dendrochronological LW and RW are very well-correlated to each other (data not shown). However, when looking at the mean correlation values and the lower EPS values, it can be observed that the individual tree series were less correlated with each other with respect to LW than was observed for RW.

3.2 Growth history - decline

In Fig. 3a, the graphs of the mean raw tree-ring series of healthy and declining trees are found and it can be observed that the RW and LW of healthy trees are usually superimposed on the mean curves of declining trees, and it is evident up to the middle of the 1940s. In the year 1945, the difference in the dendrochronological behaviour reaches a minimum value, and after the 1950s, there is a further flattening with a more evident approach between healthy and declining curves. After 1980, the dendrochronological raw series of healthy and declining trees are almost overlapping.

The most important minimum pointer years (Table 3) fell in 1945, 1952, 1955, 1971, 1973, 1982, 1989, 1999, 2002, 2006, and 2007. They are represented in both healthy and declining trees and there are strong minimums with recurrent negative minimum widths after the 2000s (cf. dendrochronological curves in fig. 3a and 3b).

3.3 Climate-growth relationships

Through the response function profiles, healthy trees demonstrated a positive correlation between RW and precipitation (Figure 4a). The climatic constraining parameter is signified by the sum of spring precipitation during April, May, and June of the current year (t), with significance at more than 99.9% in the partial regression coefficient. A remarkable effect was also determined from the sum of the precipitation recorded in October, November and December of the previous year (t-1). In declining trees, the response of RW to precipitation is very similar to that of healthy trees.

The most remarkable difference in RW response functions to climate for declining trees was the temperature signal (Fig. 4a). Declining trees were much more sensitive to the mean minimum temperature of April-May-June-July (negative correlation) and, overall, to the mean maximum temperatures of the months of February and March.

The response function of LW (Figure 4b) was very similar to RW in terms of partial regression coefficients, although the overall significance was lower, especially in declining trees. It must be remarked that the inverse relationship of LW in declining and healthy trees with the minimum temperature was prolonged to the month of August.

Comparing the departures from the rainfall of April-May-June with the RW dendrochronological series, both in healthy and declining trees, a strong coincidence between dry and rainy years with minimum and maximum widths, respectively, of both tissues (RW and LW) was noted. In Figures 5a and 5c, RW is compared in healthy and declining trees with the total April, May, and June precipitation.

Figure 4. Response functions between the climate parameters of precipitation and temperature for the period 1925-2013. The matrices precipitation-maximum temperature (PTMAX) and precipitation-minimum temperature (PTMIN) with 17 regressors were related by the bootstrap method to (a) mean total RW and (b) LW width by distinguishing healthy and declining trees (residuals obtained by standardized data and then applying ARMA processing). * P>95%, ** P>99%, P>99,9%.

Figure 5 The value (or index) of tree ring width (RWI) of healthy (*left*) and declining (*right*) trees (red-dotted line) are reported after detrending by a spline model with time lag of 11 years that was applied. The index of healthy and declining trees was, respectively, compared with total precipitation (blue solid line) of April-May-June (a,c) and the mean minimum temperature of April, May, June, and July (e,g). Precipitation (green solid line) and index values (orange-dotted line) are compared after fitting a trend curve of a moving average of five years (b,d). The same process was applied to standardized values of ring width (RW) related to mean minimum temperature (f, h).

Looking at the superimposed moving average trend curve (Figures 5b, d, f and h), we can observe a favourable climatic period at the beginning of the 1940s because of conspicuous precipitation with an abrupt strong period of drought beginning in the following years (1943-1944) as well as a very deep minimum in 1945. From this perspective, looking at the positive extreme events (Table 4b), the years 1941-1944 were evidently featured both healthy and declining trees, potentially being positively affected by temperatures which are lower than the average (for the negative correlation temperature and ring width) and precipitation higher that the average in 1941 (positive correlation ring width and precipitation). The extreme climatic events in the limiting factors establish, affecting negatively growth find a correspondence both referring to healthy trees and declining ones. Noteworthy is the high number of extreme event in temperature values after 2000 (very high temperatures) which exhibit a strict adherence to extreme minimum in growth (Table 4a).

Further information came from the piecewise test, in particular the positive change in the slope of the AMJJ minimum temperatures occurring in 1980 (Figure 6c), but only 13 years later, in 1993, there are the negative slope breakpoints in declining series (Figure 6b), while in healthy trees, the same phenomenon is observed four years later in 1997 (Figure 6a). With regards to precipitation, the only remarkable change in slope is the breakpoint at 1941 and then the abrupt fall in 1943 (Fig. 6d),

Fig. 6 Piecewise Test applied to: 6a standardized series of healthy trees where three breakpoint are distinguished in 1) 1925-1942 (y = 0.063x – 121.42 R^2=0.76), 2) 1943-1945 (y=0.26x+506.6 R^2=0.99), 3) 1946-1997 (y=0.0035x-5.83 R^2=0.071), 4) 1998-2013 (y=0.042x+84.91 R^2=0.73); 6b standardized series of declining trees where three breakpoint are distinguished in 1) 1925-1943 (y=0.0602x – 115.2 R^2=0.75) 2), 1944-1945 (y=1.0008x – 0.4911 R^2=1), 3) 1946-1993 (y=0.0059x-10.58 R^2=0.15), 4) 1994-2013 (y=0.0311x+63.17 R^2=0.59). 6c minimum temperature of April-July One breakpoint is visible 1) 1925-1980 (y=-0.0021x+19.03 R^2=0.0041), 2) 1981-2013 (y=0.06x-103.56 R^2=0.49); 6d sum of precipitation of April-June no breakpoint is visible (y=0.025x+74.42 R^2=0.0001)

Table 3. Pointer years in ring widths

Table 4 Remarkable years due to negative (a) and positive (b) extreme events affecting tree growth are reported. In both cases ring widths index of healthy and declining trees are respectively related to minimum temperatures of April, May, June, July (AMJJ) (negative correlation) and precipitation of April, May, June (AMJ) (positive correlation).

3.4 Aerial photographs

From the available historical aerial photographs, corresponding to four scenarios - 1945, 1959, 1980, and 2000 - it is not possible to glean information on dead trees or the vitality of the tree crown. However, it is possible to generate ideas about the density of the forest canopy and stand competition, which are factors that affect the efficiency of the water available resources . In 1940, the canopy was not very dense, and it is possible to see the bare soil. During that period, which corresponds to the end of WWII, it is likely that the populations' need for firewood was reflected in the lack of shrubs in the understory canopy as can be inferred by the potential for distinguishing the bare ground in the aerial photograph (Figure 7a). At the end of the 1950s, there was an increase in the density of the canopy and it is possible to see an understory layer and a dominant layer; in this period, no forest management has been reported (Figure 7b). The evolution of the canopy remained the same up to the end of 1980, when it appears uniform and only a dominant layer can be observed (Figure 7c). By this point, the stand could be considered mature and characterised by stronger tree competition.

Comparing the aerial photographs of 1992 (Fig. 8a) with the stressing period after 2000 (2005, 2016) (Fig. 8b and 8c); it is evident there is a strong increase in dead trees in the Estate.

Figure 7 (a) Aerial photograph, 1945; (b) aerial photograph, 1959; (c) aerial photograph, 1980; and (d) aerial photograph, 2000.

Figure 8. Castelporziano native broadleaf oak woodland: photographic interpretation of dead oaks detected in the three considered temporal scenarios (dead oaks are signified by yellow, red, and blue dots for the three considered scenarios).

4 Discussion

4.1 Impact of climate on tree growth

The growth-climate relationships of deciduous oaks in Castelporziano established in this work fit very well with the previous studies on deciduous oaks in the same area (Corona et al. 1995;

Romagnoli and Codipietro 1996; Amorini et al. 1996; Di Filippo et al. 2010). The strong and positive influence of spring precipitation of the current year on RW and LW was indeed confirmed. The sensitivity to spring precipitation confirms the typical character of oak deciduous species because it is even more pronounced in wetter environments (Lebourgeois et al. 2004, 2006; Drobyshev et al. 2007b; Helama et al. 2009; Andersson et al. 2011; Gillner et al. 2013).

Similarly, water availability in the autumn of the year, t-1, has a remarkable influence (Corona et al. 1995; Romagnoli and Codipietro 1996; Di Filippo et al. 2010). This correlation must be related to the potential of accumulating water reserves in the soil that will promote greater root growth (Lebourgeois et al. 2004) for the following year or in the accumulation of carbon in C-stores in buds (Barbaroux et al. 2003). Remarkable signals in response functions in Castelporziano are identified in the negative correlation of RW and LW with warm spring and summer temperatures, which may increase evapo-transpiration rates. The negative effect of temperatures in October of the year, t-1, in RW of healthy trees might be related to a prolonging of the vegetative season which did not enable the accumulation of carbohydrates, acting as energy reserves for the following growing season (Andersson et al. 2011).

Reviewing the superimposed graph of precipitation and temperature, we can observe a high correspondence between minimum and maximum width values and climatic parameters of the limiting months for growth (dry April-May-June; warm April-May-June-July). Among positive peaks based on high precipitation rates, we underscore 1956 and 1967; the peak for the latter is found in a wide geographical range as was that for 1991 (Lebourgeois et al. 2004; Drobyshev et al. 2007b). Among the minimum pointer years of wider geographical relevance, 1984 was also as cited by Moretti et al. (2015) as it was particularly important for the Mediterranean area. With respect to minimum widths, we highlight 1945, 1952, 1955, 1962, 1971, 1982, 1987, 1993, 1999, 2007, and 2011 with high spring-summer temperatures and/or low spring precipitation. Among the pointer years 1955, 2007 and 2011 correspond to very unfavourable extreme climatic events (cf. tab. 4a) which are to be observed in very low ring width in the chronological curve (Fig. 3a). The year 2007 has a wide significance, because it exhibited low growth in oaks in Central Europe also because of pronounced drought (Tumajer and Treml 2016). In that year, there was a significant reduction in the underground water table in Castelporziano (Mastrorillo and Petitta 2013). From the 2000s, there were several dry years (2006-2007) and years with temperatures above the average (2003 and 2008-2009) (Moretti et al. 2015), which were considered stressed according to the definition of Rammig et al. (2015) and this might be a main reason for growth decreasing and the clear evidence of dieback.

4.2 Growth history and decline

Based on our assumption, we expected different dendrochronological behaviours between healthy trees and declining trees by means of signals describing a reduced crown vitality. This hypothesis was not demonstrated at all since the dendrochronological curve of healthy trees (raw data) is superimposed to the declining ones up to the middle of the 1940s, but it might be due to the younger age of healthy trees. Indexed data are consistent with this scenario, because after removing the effect of age the dendrochronological curves overlap much more. Much debate has concentrated on the role played by age in the oak decline process because it has been considered of secondary importance (Biondi and Qeadan 2008; Natalini et al. 2016). From the results, it could be assumed that age exacerbates dieback signals in RW raw data by expediting or anticipating the decline phenomenon (Rozas 2005; Corcuera et al. 2006; Voelker et al. 2008). The hypothesis was not confirmed by Kruskal Wallis testing, which does not report any significant statistical differences between age, so as in DBH, RW means value, mean sensitivity, and LW width when comparing healthy and declining trees (data not shown). Neverthless it must be kept in mind that the lack of statistical significance could be due to the limited sampling.

Climate is of fundamental importance in determining dieback. The effect of the dry period between 1943-1945 is visible via multi-year growth declines (Tulik 2014; Berdanier and Clark 2016; Panayotov et al. 2016), a period where oaks were able to withstand thanks to their deep root system and the low competition within the canopy at that time. The dry period of the middle of the 1940s in

Central and Northern Europe has also been referred to as one of the main reasons behind oak decline (Rozas and Sampedro 2013). A further relevant decreasing period dates back to the dry period between 1981-1989 (Fig. 5). The decade of the 1980s was considered quite detrimental in terms of oak decline both at different European sites, such as the Iberian Peninsula (Corcuera et al. 2004; Natalini et al 2016), and elsewhere in the Latium Region (Amorini et al. 1996; Di Filippo et al. 2010. Drought can be considered one of the main factors behind oak growth decline, induced by low precipitation and primarily by high minimum temperatures and the most important driver that reduces crown vitality and fosters tree mortality (Allen et al. 2010; Natalini et al. 2016).

Tree mortality attributed to drought is because of the phenomena of cavitation, or embolism, which is a peculiar occurrence in deciduous oaks because of their wide cross-sectional area of vessels in porous zones of the ring (Lo Gullo et al. 1995). Temperature and physiological stress increased after 2000, especially after there was an increasing prevalence of mortality exacerbated by high competition in the canopy, which would lead to reduced availability of essential nutrients, potentially amplifying the vulnerability of trees to additional stresses (Rozas and Sampedro 2013).

With respect to this point of view, oak decline studies have seldom pointed out drought as the only factor that induces oak mortality (Thomas et al. 2002). We are in agreement that unfavourable habitat changes, i.e., tree competition (Drobyshev et al. 2008; Andersson et al. 2011) within stands, are further relevant drivers of decline, connecting also with the age of the stands (Di Filippo et al., 2010). Furthermore, the Castelporziano site is subject to intensive grazing, an additional threat to the fertility of the soil. The role of urbanization in the area is fundamental because the resident population has doubled every 30 years (Recanatesi 2015). Starting in the early 1950s, to date, the whole area surrounding the estate is full of crowded settlements. Fragmentation of the landscape is often reported as one of the most determinant causes of vulnerability to climatic changes (Ordóñez and Duinker 2014).

Ring width decline has showed to start decades before symptoms are noticed (Catton et al., 2007) , so we can expect the trees now classified healthy in a near future will show dieback symptom in the crown. The lagged impact of drought on decreasing growth changes has been showed more times (Di Filippo et al. 2010; Vanoni et al. 2016) and it depends on stand history and canopy (Andersson et al. 2011; Di Filippo et al., 2010); in the case of Castelporziano, and according to Fig. 6, we can estimate a interval of 13 years (in older trees) before decreasing in growth after the changes in increasing temperature and at least four years (17 years) later in the classified healthy trees (that are also younger). Dieback can be a decade-long process and oak decline is an example of the complex process in which the phenotypic response of trees regarding to climate is not immediate and depends by many factors.

4.3 Latewood width

Generally, mean sensitivity values were higher by roughly 0.2 for the whole Castelporziano site both for healthy and declining trees and it was also higher for LW than in RW; this leads to the expectation of the role of LW as a more sensitive parameter to environmental factors (Romagnoli and Codipietro 1996; Lebourgeois et al. 2004).

Climate-growth relationships, as elaborated by response functions, were more significant in RW than in LW and in healthy trees versus those in decline. At Castelporziano, the two dendrochronological series were well correlated to each other and their climate-growth relationships were quite similar. LW is a very central factor in the oak decline process because LW vessels have been demonstrated to assume the role of functional conduits supporting water flow in trees (Tulik 2014). They are also less prone to cavitation that takes place mainly in earlywood (Lo Gullo et al. 1995; Corcuera et al. 2006). Therefore, because very dry years reduce crown vitality and there is no LW production at all (Corcuera et al. 2004), the trees become much more vulnerable to the risk of cavitation. In this scenario, age must be considered because the most recently formed rings are also distinguished by a higher proportion of earlywood.

5 Conclusions

The growth history of healthy and trend in declining deciduous oaks at Castelporziano, assessed according to their crown vitality, are very similar, meaning it must be reasonably expected that over the next years, a declining scenario will be evident and encompass all deciduous oaks widespread throughout the area. The cause of the decline can be related to drought. Warm and dry years, especially when they act together during limiting months on growth, compromise tree health and survival. The onset of decline dates back to the middle of the 1940s, it increases in 1980, and is exacerbated by the recurrent extreme events of high minimum temperature after 2000. Dieback at Castelporziano is worsened by human pressure driven by Rome's expansion. The role of stand canopy cannot be neglected after 1980 because it limits water availability and water use efficiency, and, as such, thinning could have potential significance because there must be a reasonable anticipation of the increase in radial growth, and it generates greater water availability for the remaining trees.

At Castelporziano, the results are quite comparable to the effects seen in other stands. This could mean that the site has become part of a network where decline and mortality must be studied at the global level. Deciduous oaks are endowed with the ability of signifying large-scale climatic changes, notwithstanding the noise factors typical of peri-urban forests located close to metropolises.

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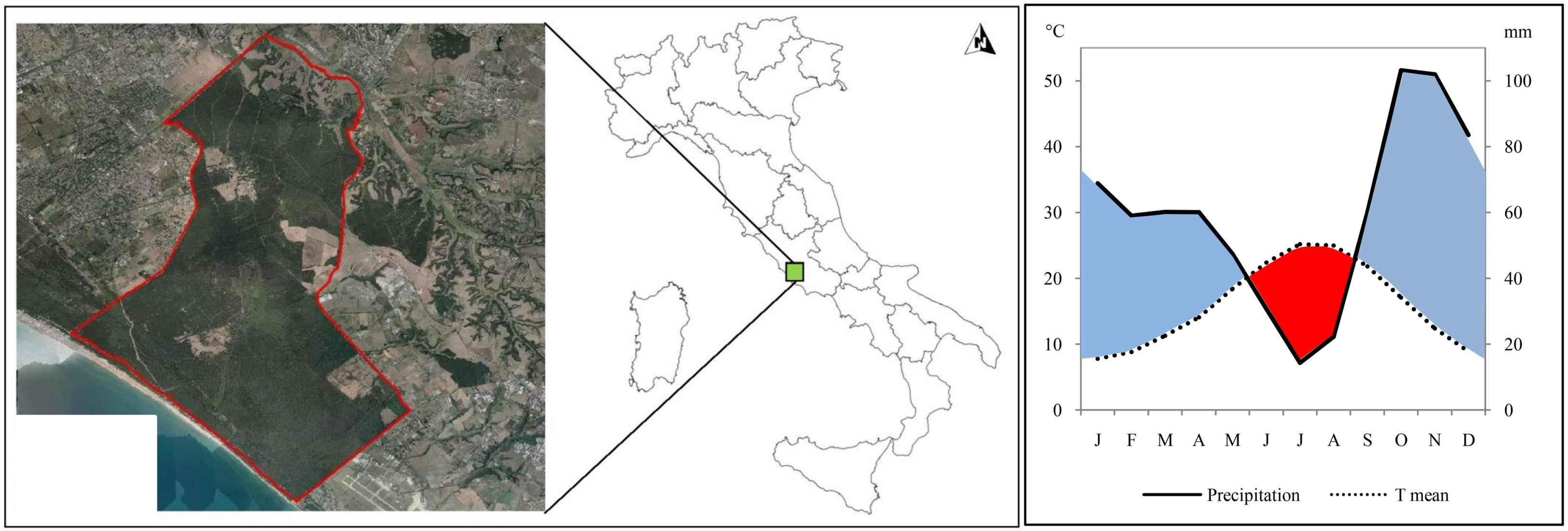
°C
mm
50
40
30
20
10
0
100
80
60
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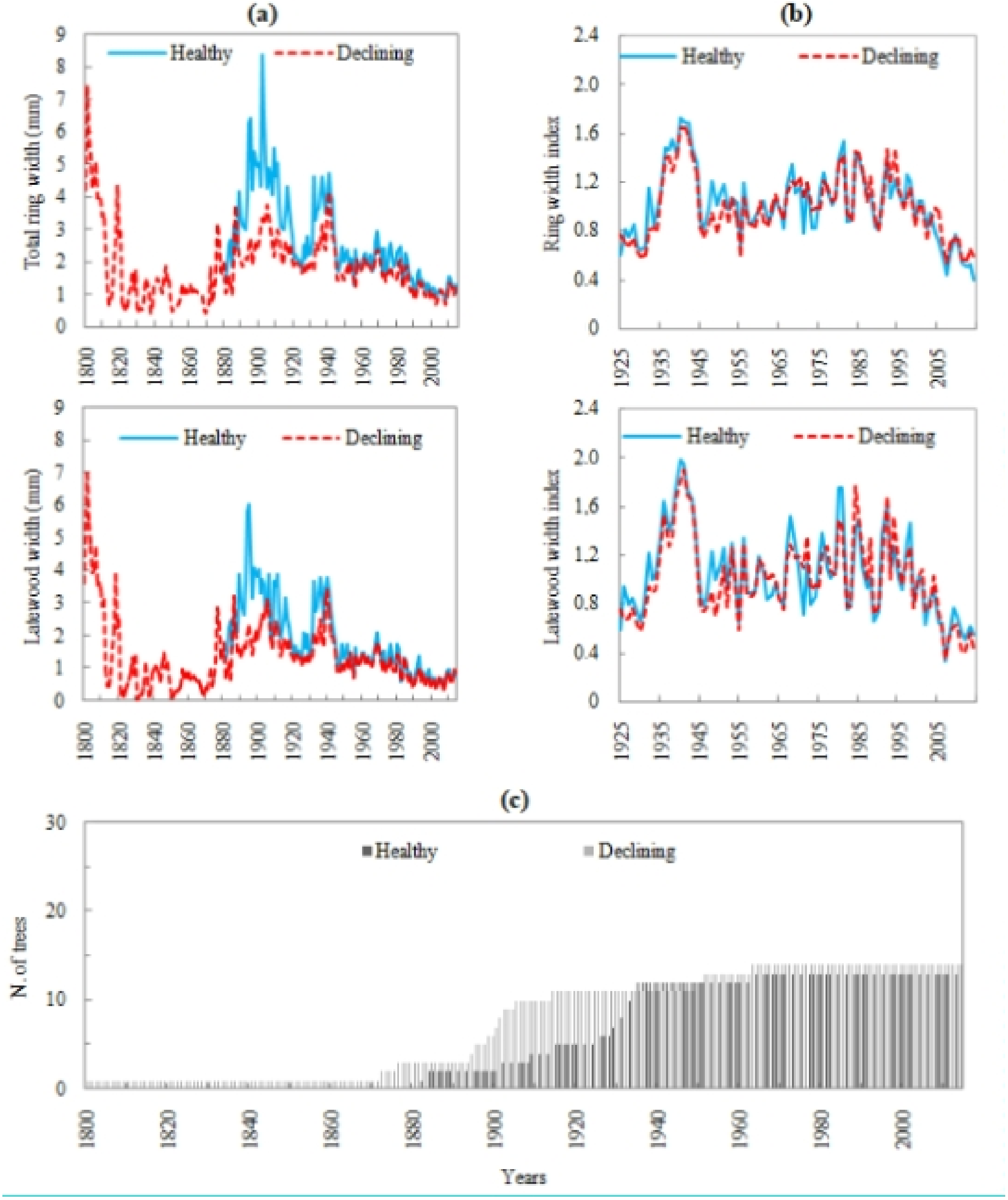
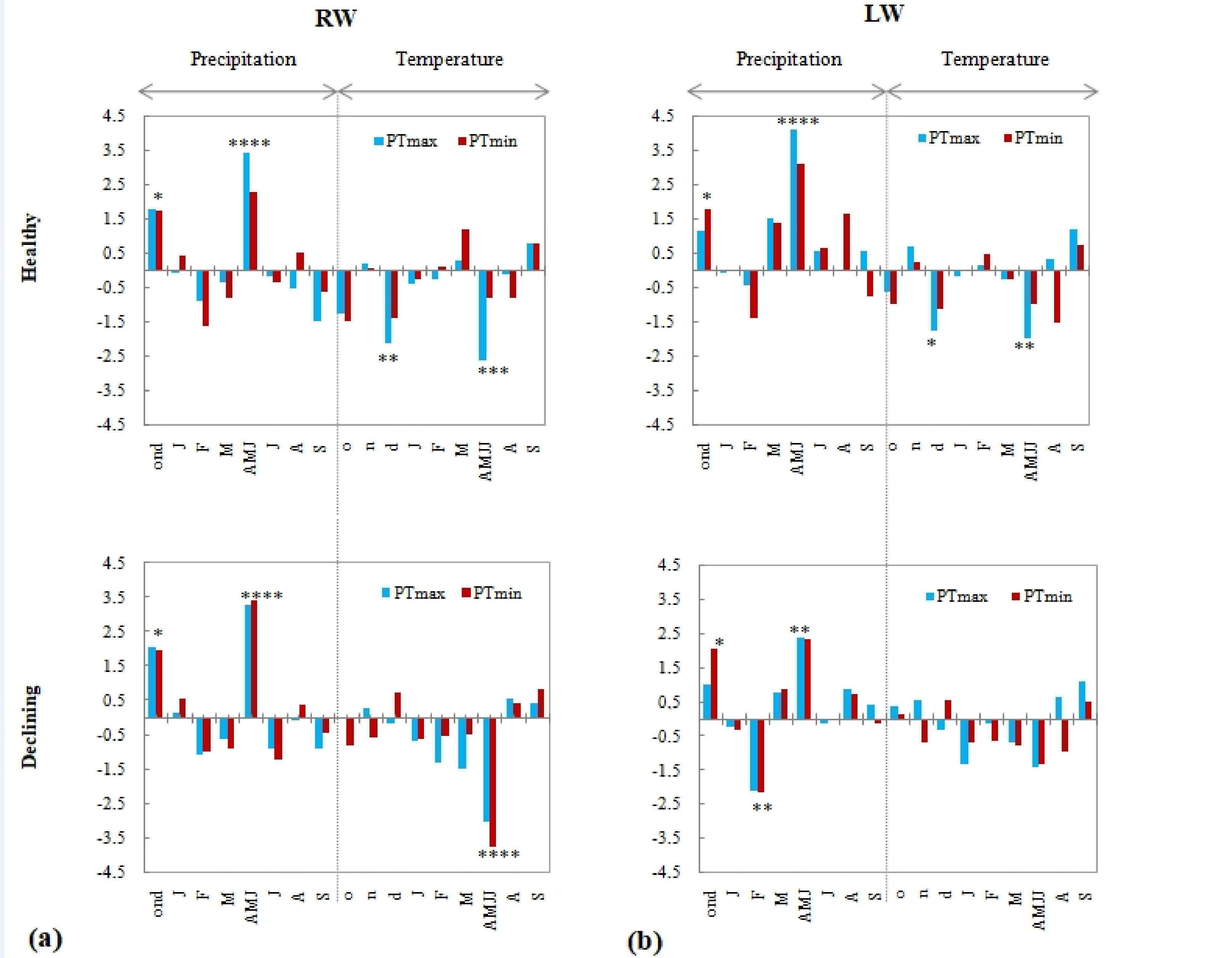
J F M A M J J A S O N D
Precipitation
T mean

(a) **(b)** **(c)** **(d)**


(a)
Healthy
Declining
Total ring width (mm)
Latewood width (mm)
(b)
Ring width index
Latewood width index
(c)
N. of trees
Years


RW
LW
Precipitation
Temperature
Healthy
Declining
PTmax
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ond
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o
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J
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M
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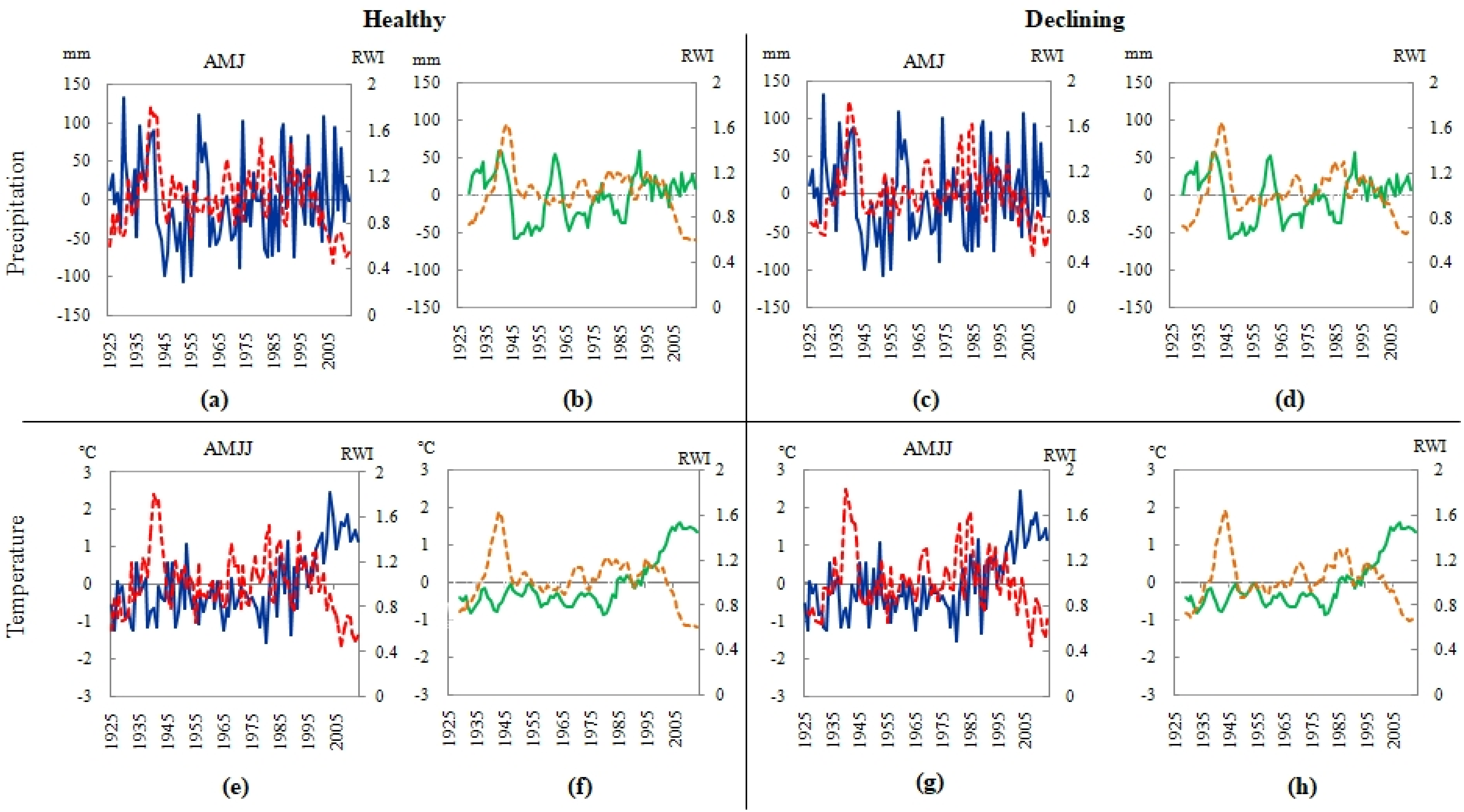
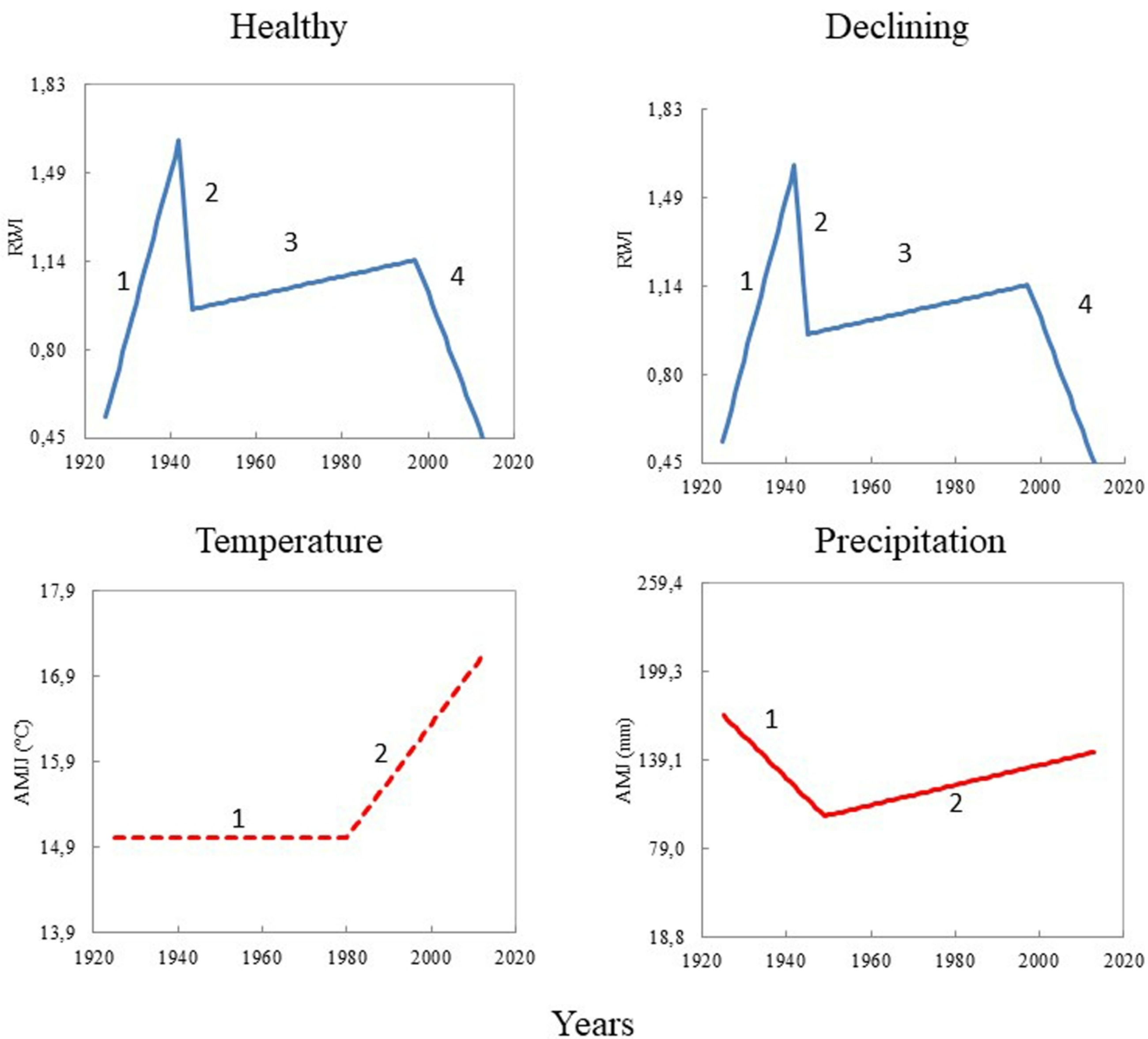
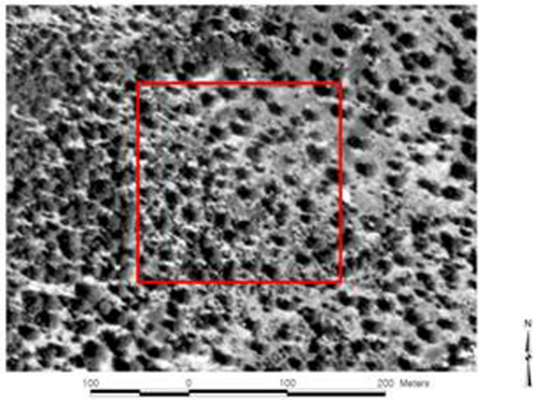
S
(a)
(b)



Healthy
Declining
Precipitation
Temperature
mm
RWI
AMJ
AMJJ
°C
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

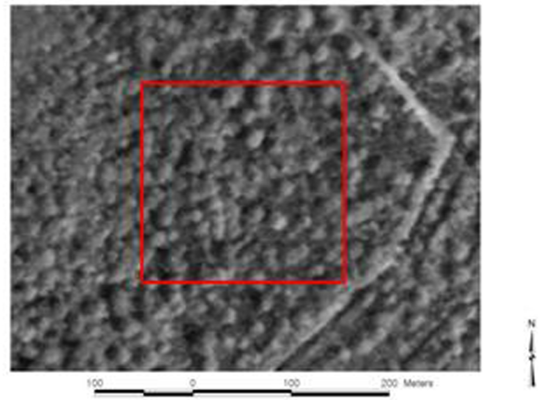

Healthy
Declining
Temperature
Precipitation
RWI
AMJJ (°C)
AMJ (mm)
1,83
1,49
1,14
0,80
0,45
17,9
16,9
15,9
14,9
13,9
259,4
199,3
139,1
79,0
18,8
1920
1940
1960
1980
2000
2020
1
2
3
4
Years

1945



(a)

1959



(b)

1980

(c)

2000

(d)

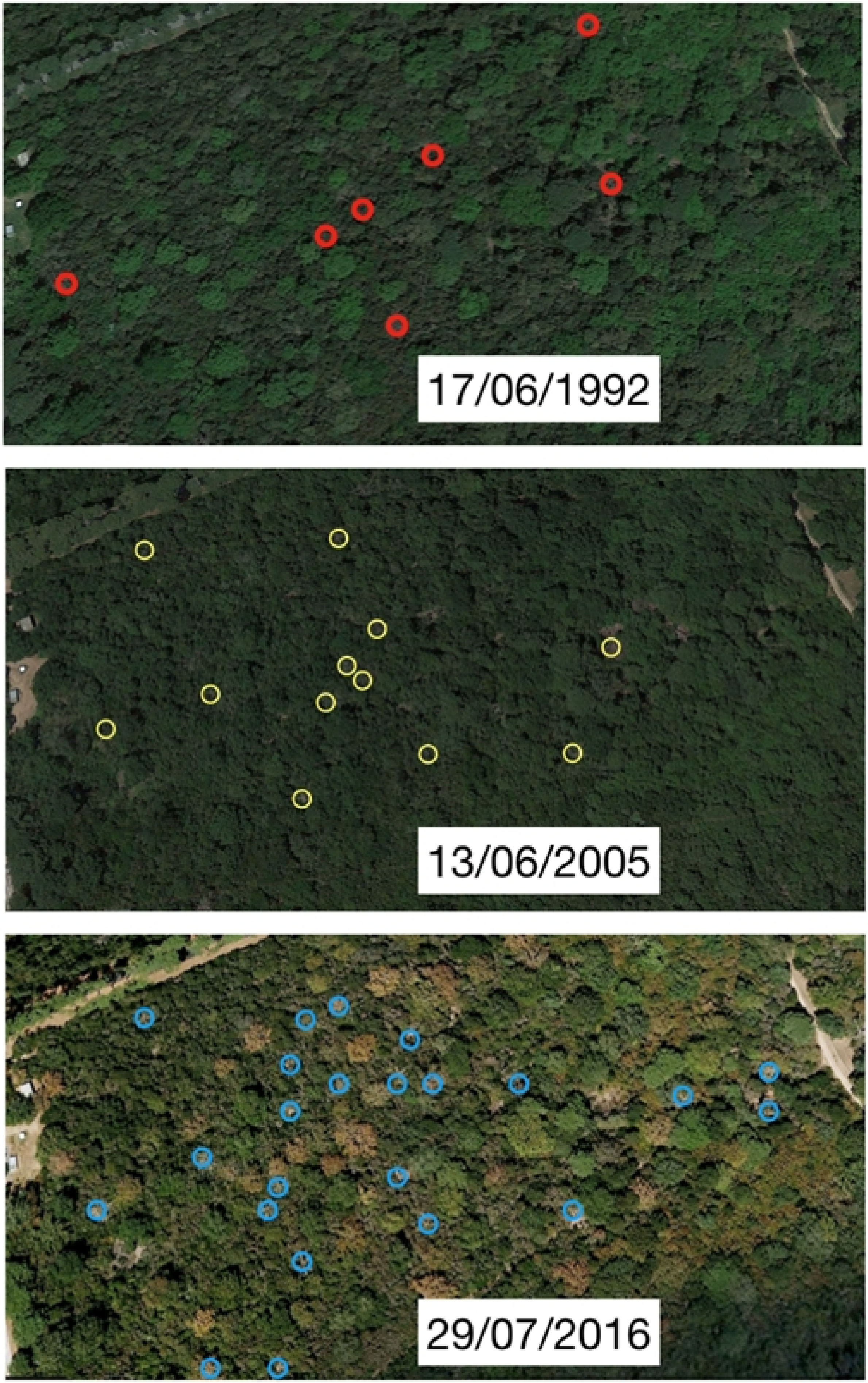

17/06/1992
13/06/2005
29/07/2016

Table 1. Number of trees classified according to vigour classes. Minimum (Min), maximum (Max), and mean value (MV) with standard deviation (SD), respectively, of diameter at breast height (DBH) and age were reported of the 26 cores suitable to be included in the mean curves.
Diameter at Breast Height and Age of the investigated trees classified according to the vigour class.

Subgenus	**Vigour classes**	**Number of trees**	**DBH** [cm]		**Age**	
			MV±SD	Min/ Max	MV±SD	Min/ Max
Cerris	Healthy	6	61.8±26.3	39.8/98.7	94±27.8	52/132
	Declining	5	60.9±22.9	26.8/ 89.8	131.2±48.3	90/ 215
Quercus	Healthy	5	58.1±12.9	36.6/ 71.7	97.2±23.1	80/ 134
	Declining	10	65.1±19.1	40.1/102.9	105±27.4	64/143

Table 2. Statistical parameters of mean tree ring width (RW) and mean latewood (LW) width for healthy and declining trees: Mean value (MV), standard deviation (SD), coefficient of variation (CV), mean sensitivity (MS), mean correlation between trees, and expressed population signal (EPS).a EPS was calculated considering the common period of 1963-2014 (52-year interval)

	Vigour classes	**Number of trees**	**MV ± SD (mm)**	**Coefficient of Variation (%)**	**Mean Sensitivity**	**Mean correlation between trees**	**Expressed population signal**[a]
RW	Healthy	11	2.59 ± 1.40	54.1	0.183	0.570	0.826
	Declining	15	1.78 ± 1.06	59.4	0.224	0.385	0.690
LW	Healthy	11	1.89 ± 1.13	59.9	0.239	0.503	0.774
	Declining	15	1.37 ± 1.01	73.7	0.298	0.309	0.625

Table 3. Pointer years in ring widths

Pointer years in ring width		
	Positive (+)	**Negative (-)**
Healthy	1926; 1932; 1936; 1947; 1956; 1967; 1972; 1975; 1976; 1984; 1991; 1997; 2008; 2013.	1927; 1929;1933; 1938; 1941; 1943;1944;1945; 1949; 1952; 1955; 1957; 1962; 1965;1969; 1971; 1973; 1977; 1978; 1982; 1987; 1993; 1995; 1999; 2002; 2007; 2011;
Declining	1932; 1936; 1956; 1967; 1980; 1984; 1991; 1994; 2000; 2004; 2008;2009; 2013.	1929; 1937; 1938; 1942; 1943; 1944; 1945; 1952; 1954; 1955; 1962; 1971; 1978; 1982; 1986; 1987; 1989; 1990; 1995; 1999; 2002: 2006; 2007; 2011;

Table 4. Remarkable years due to negative (a) and positive (b) extreme events affecting tree growth are reported. In both cases ring widths index of healthy and declining trees are respectively related to minimum temperatures of April, May, June, July (AMJJ) (negative correlation) and precipitation of April, May, June (AMJ) (positive correlation).

Extreme negative ring widths (-) and related extreme climatic parameters			
Ring Width Index (RWI)		**Minimum temperatures** (AMJJ)	**Precipitation** (AMJ)
Healthy	Declining		
1929	2007	2003	1952
1955	2012	2004	1945
2006	2013	2009	1955
2008	2008	2007	1973
1925	1930	2008	1993
2011	2011	2012	1983
2013	2009	2000	1985
2012	1931	2011	1946
2007	2006	1988	1987

(a)

Extreme positive ring widths (+) and related extreme climatic parameters			
Ring Width Index (RWI)		**Minimum temperatures** (AMJJ)	**Precipitation** (AMJ)
Healthy	Declining		
1940	1941	1980	1930
1942	1942	1989	1958
1941	1940	1965	2004
1981	1943	1933	1974
1939	1981	1926	1989
1992	1944	1978	1936
1980	1994	1948	2008
1943	1992	1941	1941
1985	1993	1938	1988

(b)