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Original article

The age of monumental olive trees (*Olea europaea*) in northeastern Spain

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ABSTRACT

Trees can reach ages that in some cases amount to thousands of years. In the Mediterranean region, olive trees (*Olea europaea*) have traditionally been considered a particularly long-lived species. The main objective of this study was to assess the age of large olive trees considered to be millenarian and classified as monumental trees in northeastern Spain. We extracted cores of 14 individuals and obtained 8 sections of trees which had already been cut in the area where the largest olive trees in the northeastern Iberian Peninsula are found. The age of the sampled olive trees was assessed by counting the number of annual growth rings. Tree rings did not cross-date well, neither within nor between individuals, but boundaries between likely annual rings were clearly distinct. We found a linear relationship between DBH and tree age (in years) ($\text{Age} = 2.11 \times \text{diameter(cm)} + 88.93$, $R^2 = 0.80$), which was used to estimate the age of unsampled olive trees. The maximum estimated age (627 ± 110 years) is among the greatest ages reported for olive trees around the world (700 years) and among the oldest trees in Mediterranean ecosystems.

Introduction

There are at least 17 species of trees in the world that can reach ages of more than 1000 years, and almost all of them are conifers (Thomas, 2003, http://www.rmtrr.org/oldlist.html). The oldest known trees (*Pinus longaeva*) live in the Rocky Mountains of North America, with ages close to 5000 years (Currey, 1965). However, if clonal plants are also considered, known ages may be even greater: *Gaylussacia brachycerium* or *Larrea tridentata* have ages of more than 10,000 years (Thomas, 2003). On the other hand, cultivated plants are often propagated via grafting, and, for example, certain varieties of very old grapes have been propagated by successive graftings for over 800 years (Nooden and Thompson, 1985).

The analysis of how tree species may react as environmental conditions alter is of major importance in the frame of global change (Bazzaz, 1996). A prerequisite for such analyses is knowledge of how forests have reacted to past climatic and anthropogenic changes. Tree rings enable us to reconstruct the responses of some plant species to environmental changes (Fritts, 2001), but such information is very scarce for many Mediterranean species (Cherubini et al., 2003). Thus, long-lived trees can be very good proxies for such analyses, because their annual resolution may permit the reconstruction of past climatic conditions with a precision that few other proxies can provide. However, the lack of ancient natural forests in the Mediterranean region due to intensive historical logging, burning and grazing explains the scarcity of dendroclimatological studies in these ecosystems.

The olive tree (*Olea europaea*) is an evergreen tree belonging to the family Oleaceae. It originated from the wild olive tree (*O. europaea* var. *sylvestris*), which was cultivated in Palestine around 6000 years ago (Terral et al., 2004). It was later spread westwards throughout the Mediterranean by the Phoenicians, the Etruscans, the Greeks and the Romans. It is believed that the cultivation of olive trees arrived in the Iberian Peninsula during the second millennium BC (Terral et al., 2004). Due to their large size (they can reach more than 3.5 m in trunk perimeter, Muñoz et al., 2004), olive trees have been frequently assigned very old ages. It is common to read and hear references to these trees as “the ancient olive trees, with ages up to 2000 years old” (Dingwall-Main, 2004, referred to as ‘olivos milenarios’ in Spain). However, we know of no scientific study supporting these claims. The maximum measured age reported in the scientific literature for this species is of around 700 years (Nooden, 1988; Thomas, 2003). But studies on the aging of olive trees are scarce. This is because the identification

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and interpretation of annual tree rings can be problematic with certain Mediterranean species such as the olive tree (Cherubini et al., 2003). Moreover, in many large olive trees the inner part is not present because of wood rotting. However, even in cases where the central part of the tree (the oldest wood) has disappeared or is poorly conserved, it is possible to estimate the age of an individual with some accuracy using the number of the most recent rings (Clark and Hallgren, 2004).

Because of their old age, olive trees are potentially good candidate species to be used as proxies for climatic reconstruction in the Mediterranean region. There are two basic conditions that tree species must satisfy so that they can be used as such proxies. Firstly, they need to have detectable annual rings. And secondly, the growth signals between various samples per tree and between various trees per site need to coincide sufficiently, thus allowing the environmental signal to be maximized and the “noise” from individual variation minimized (Fritts, 2001).

Traditional olive crops are currently suffering a major setback. This is because olive trees are being removed from the most fertile soils to be interchanged with more profitable crops. Furthermore monumental olive trees are currently being traded as ornamental trees in a business that is expanding (Fos Martin, 2006). It is important in this context to consider the scientific, social, and cultural value of olive trees, which makes them a basic target of conservation programs.

The main objective of this work was to increase our knowledge about a unique set of monumental olive trees in northeastern Spain, which contain the largest trees in the region. More specifically, we wanted to: (a) determine the age of some of the largest olive trees in the region; (b) establish the relationship between the age of an olive tree and easily measurable biometrics, in order to provide an allometric method to estimate with some precision the age of other monumental olive trees; and (c) investigate the possibility of carrying out dendroclimatological studies with olive trees.

Materials and methods

Study area

The Montsià region (Catalonia, Spain) is characterized by the omnipresence of olive cultivation, which is evident in all open spaces ranging from the coastal plains to the slopes of various mountain ranges. The largest concentration olive trees is found in the Sènia river basin, in the foothills of the Serra de Godall. As in many other areas of the Mediterranean, the cultivation of olive trees is a key value in the region, both from an economic, social and scenic point of view, and has become a defining element of the landscape. This study was conducted primarily in the Arion farm (40°37′36″N, 0°25′28″E, 195 masl), a property that contains the largest, and likely the oldest, trees in the region. Olive trees from this farm have never been watered in the last 50 years, but they have been pruned once a year (in March). Although this is a common practice in most olive orchards (Muñoz et al., 2004), pruning could certainly condition tree ring width, depending on its intensity and frequency, and individual differences of this practice could result in low common climatic signal.

Sampling

Wood samples consisted of tree cores of 14 different olive trees, and sections of 8 trees that were cut in 1995 in another nearby farm. Field sampling was carried out between November 2007 and April 2008. Tree cores were extracted at a mean height of 80 cm, and sections were cut at a mean height of 40 cm. For each tree sampled, diameter including bark at 40 cm, at extraction height, and at 130 cm (DBH), was measured. Due to the high irregularity of the trunks, cores were extracted from different orientations. The center of the stem was often completely decomposed in the biggest trees (this was the case in 15 of the 22 trees analyzed), forming large cavities and preventing us from reaching the pith of the tree.

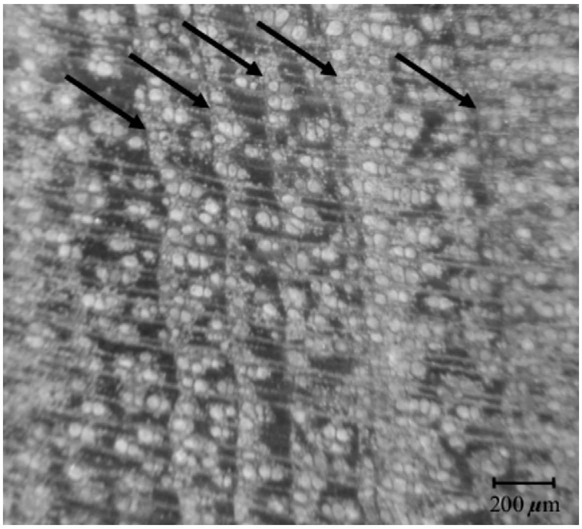

Fig. 1. Transverse section of one of the olive wood samples showing distinct ring boundaries. Arrows indicate the limits of some tree rings.

The extraction of tree cores was very difficult due to the hardness of the wood. We tried different methods, including the use of a mechanical drill (TED262Rw Tanaka, Tanaka Kogyo Co., Ltd., Narashino-shi, Chiba, Japan; see Lopez et al., 2006) with a purpose-built adapter to connect the Pressler borers. Since this was unsuccessful, Pressler borers (5–12 mm in diameter by 40–80 cm in length, depending on the dimensions of the tree) were inserted manually to obtain the wood samples. This was also very costly in terms of time and effort.

The cores obtained were placed in wooden guides and were left to dry. Afterwards, both the cores and the sections were polished with papers of different grain sizes (60–1500), until tree rings were distinct. The growth rings of each sample were identified and dated from the cortex to the pith using a stereomicroscope (Olympus SZ61, Tokyo, Japan). In transverse section, olive wood is diffuse-porous with numerous vessels, which are isolated or grouped in radial lines; it has uni- to biseriate rays and paratracheal parenchyma (Terral, 2000; http://insidewood.lib.ncsu.edu/links). Although some growth rings were probably missed (Terral, 2000), it was possible to detect them because rings are usually separated by visible parenchyma bands (Fig. 1). The samples were then scanned at a resolution of 1600 dpi using an Epson Expression 1640 XL scanner. With this resolution, the scanner yields a precision of 0.016 mm (pixel size). Growth rings were measured using WinDendro (Regent Instruments Inc., Canada) from marks that had been previously drawn manually on the thin layer of parenchyma cells while observing the samples under the stereomicroscope. Ring-width data were cross-dated with COFECHA, a quality control program used to check the cross-dating and the overall quality of tree-ring chronologies (Grissino-Mayer, 2001).

Data analysis

A linear regression with a confidence interval of 95% was calculated between the number of rings of those samples that reached the pith and the DBH of the corresponding tree. The DBH of the

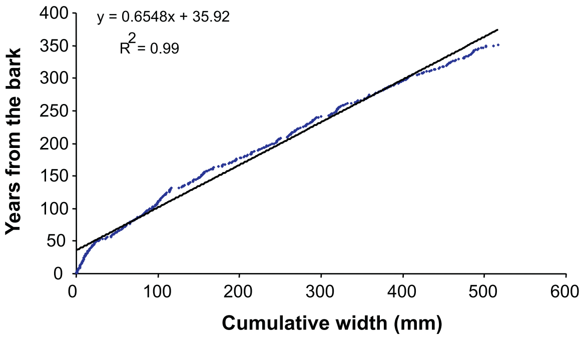

Fig. 2. Cumulative growth of one of the sampled olive trees.

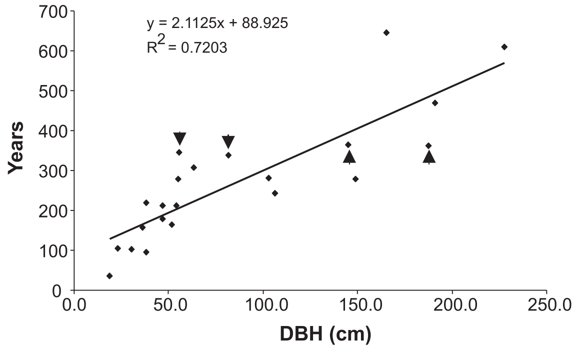

Fig. 3. Regression function used to predict the age of trees (years) from their DBH (cm). This equation was obtained from 22 samples (14 cores and 8 sections). Range of DBH values used to obtain this equation was 37–645 cm. Points with an arrow indicate samples which probably had more than one center (see text).

sections was calculated using the relationship between the diameter at 40 cm and at 130 cm of 12 living trees. Two methods were used to estimate the age of those trees whose core did not reach the center. The first method estimated the number of lost rings to the pith (N) using the following equation:

$$N = \frac{R - L}{G}$$

where G is the average thickness of each ring in the sample; L is the length of the sample that could be read, and R is the radius of the tree at the extraction height (Clark and Hallgren, 2004). The total age was estimated by adding N to the number of visible rings in the sample. Prior to this we analyzed whether the size of the rings varied with their position in the sample. A linear regression between year and ring width was calculated for the cores and the sections where the pith was visible. This relationship was significant in only one sample with the most internal rings being thinner. Consequently, the average ring width of the sample was used for the above equation. The second method consisted in predicting the number of rings (i.e., years) for the maximum radius of the olive tree using a function that related the number of rings and their cumulative width for each of the samples by simple linear regressions (Clark and Hallgren, 2004) (Fig. 2). As the values calculated by these two methods were similar in all cases (t-tests for paired samples: $t = -0.129$, $p = 0.899$, d.f. = 17) we used the mean of the two values obtained to estimate the age of the olive trees.

Results and discussion

Tree rings were highly variable in width, both within and between individuals, and so correlations between these series were not expected to be significant. Cross-dating analyses with COFECHA showed that the correlations among individuals were all close to zero. Also, the relatively high sensitivity indicated great variability between rings of the same series. This is mainly due to considerable deformation of the stems, which makes the thickness of the rings highly variable depending on the side of the stem from where the core was extracted. Another explanation may be that the different trees sampled might have been managed in various ways in the past, and different spacing among trees, pruning or fertilization could have conditioned tree growth (Terral and Durand, 2006). Whatever the case, this outcome has two main consequences. On the one hand, since the series do not crossdate, it is impossible to build a master series. Therefore dendroclimatic reconstructions based on major environmental signals would be very difficult to carry out using master series as proxies. And, on the other hand, it is difficult to know to what extent the number of detected rings really corresponds to the age of the trees, because we have no way of controlling for missing or double rings. Nevertheless, the rings were generally quite easily detected after proper polishing. Moreover, when comparing paths of the same sections, and manually following each ring from one path to another, it was evident that the problem was not the detection of rings but their high variability in width (Terral and Arnold-Simard, 1996; Terral, 2000).

Some additional problems were detected. Firstly, the olive trees were not always concentric, i.e. the geometric center did not necessarily match the chronological center (Terral and Arnold-Simard, 1996; Terral, 2000). This could cause a problem when estimating the age of the sampled olive trees using the Pressler borer. This problem would affect the precision of our estimation, increasing its variability (Clark and Hallgren, 2004). However, this should not affect the accuracy, because the sampling method did not introduce any bias due to this factor. Thus, on average, the estimated ages should be correct. Secondly, it was observed that some wood samples contained more than one center, indicating that the tree originally consisted of more than one stem. This is potentially a more important problem, because in this case, the chronological radius is much smaller than the geometric radius and, therefore, the age of trees cannot be calculated from this radius. To solve this problem, those cores with lengths lower than the geometric radius divided by 2 were discarded. In this way, we eliminated those samples (four in total) in which individuals were more likely to be multi-stemmed.

The DBH of the sampled trees (tree cores) ranged between 18 and 228 cm, with estimated ages between 37 and 645 years. On the other hand, the sections had calculated DBH values between 36 and 64 cm, with estimated ages between 94 and 307 years. Considering both kind of samples together, there was a significant positive linear relationship between DBH and age ($F = 51.5$, $p < 0001$; $\beta = 0.849$, $R^2 = 0.72$, $n = 22$, Fig. 3). The parameters of this relationship did not change if the samples which were likely to be multistemmed (see above) were excluded from the analysis, but the R^2 increased to 0.80.

The DBH of the unsampled monumental olive trees ranged between 127 and 255 cm, with estimated ages between 358 ± 45 and 627 ± 110 years (95% confidence interval) (Table 1). Thus, these olive trees, with maximum estimated ages of up to 650 years (with a range of 313–737 years, including the age of the oldest olive trees measured), are among the oldest dated trees in the Mediterranean and probably in Europe (http://www.rmtrr.org/oldlist.html). These ages are quite unique, as very few species of angiosperms reach ages close to 1000 years (Thomas, 2003). The maximum estimated ages in this work are very similar to those of the oldest dated olive trees measured worldwide (around 700 years, Thomas, 2003). It is interesting to note that the estimated ages of olive trees in northeastern Spain implies an establishment period which roughly coincides with the end of the Little Ice Age that occurred in the

Table 1
Predicted age (in years) of 12 representative olive trees from their DBH. This prediction was carreid out using the relation between the measured age of some individuals and their DBH (Fig. 2), with a confidence interval of 95%.

DBH (cm)	Predicted age	Lower limit	Upper limit
254.6[a]	627	517	736
191.0	492	418	566
184.6	479	408	550
179.2	468	400	535
173.5	455	391	520
165.5	439	378	500
151.2	408	354	463
144.8	395	343	446
144.2	394	342	445
141.6	388	338	438
128.9	361	316	407
127.3	358	313	403

[a] This is the largest tree in the region.

Iberian Pensinsula (Martín-Puertas et al., 2008). Thus, the end of this cold period could have favored the establishment of some of the olive trees still living to date.

In conclusion, this study confirms the old age of the olive trees in northeastern Spain, particularly in the Montsià region, and situates these trees among the oldest dated angiosperms in Europe. The scientific value of these ancient trees is noteworthy, both for the study of aging in plants, and from the perspective of paleoecology. In the present times, the landscape shaped by the cultivation of olives is undergoing a profound change. This change is due to the low economic profitability of farming, the replacement of traditional crops by intensive agriculture, the implementation of irrigation systems, and finally, due to the sale of the biggest olive trees for gardening (Fos Martin, 2006). These olive trees are living archives, and although we were not successful in extracting dendroclimatological information from them, it is likely that in future we can extract valuable information on the history of local weather, or on the history of the cultivation of olive trees in the area. A promising step forward would be the use of stable isotopes, specifically δ^{13}C, which can be used for dating problematic wood samples as well as for gaining climatic information with intra-annual resolution in Mediterranean ecosystems (McCarroll and Loader, 2004; De Micco et al., 2007; Battipaglia et al., 2010).

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