Bio-archaeological evidence of olive tree (*Olea europaea* L.) irrigation during the Middle Ages in Southern France and North Eastern Spain

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Abstract

Quantitative eco-anatomical analyses were carried out on charred wood from modern olive trees (*Olea europaea* L.) in order to quantify influence of irrigation on wood characters and to detect irrigated olive specimens among charcoal assemblages dating back to the Middle Ages.

Data have been treated by multivariate statistical analysis and tests were performed in order to discriminate olive samples according to water supply. Results have shown that it is possible, not only to discriminate between wild and cultivated olive as demonstrated previously, but also to distinguish irrigated trees from those cultivated in dry conditions. Differences are discussed in term of ecological and eco-physiological responses of wood anatomy.

Finally, data thus obtained were applied to charcoal fragments from three Medieval sites (9th–15th centuries AD), revealing that irrigation practises were currently employed to olive trees. Although well adapted to a dry Mediterranean climate, olive trees were irrigated aiming to increase productivity and quality of fruit and oil. This is the first ever evidence of irrigation of fruit trees based on a bio-archaeological approach.

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1. Introduction

Throughout their life, trees must adapt themselves to possible environmental variations. Wood anatomy is influenced by any local event taking place during plant growth. Climate and anthropogenic activities are the most important factors affecting wood anatomy. Thanks to the progress and development of techniques and methods of image analysis and morphometrics, these parameters are measurable on living or/and ancient plant wood remains (charcoal) with the assistance of the methodology of quantitative eco-anatomy [23].

The principle of quantitative eco-anatomy consists in measuring vascular elements of wood and aims to understand their variations according to external parameters, both natural and/or anthropogenic.

As a result, this method allows high resolution analysis of wood structure in order to improve and enlarge our knowledge of cambium functioning, tree growth and development, pheno-ology and ecology, climate changes, impact of human activities and history of plant cultivation, domestication and agricultural practises (see for example [3,8,22,24,26]).

Among agricultural practises and developments which may be investigated through quantitative eco-anatomy, irrigation is one of the most important, especially in dry and semi-arid bioclimatic contexts such as Mediterranean areas. Since the emergence of agriculture which has constituted a ‘revolution’ in the development of societies and civilisations, irrigation is an innovation allowing to practise an intensive and productive agriculture. Climatic, demographic and economic factors are some of the many factors which lead to the expansion of irrigation, and the establishment of an intensive agriculture.
Irrigation is attested for the first time before 5000 years BC in Mesopotamia [17]. The Islamic civilisation is believed to have modernized irrigation techniques on the basis of technological practises of the Ancient world [12]. During the Islamic conquest (7–8th centuries), Roman techniques of irrigation such as basins, canals and dams for water storage, drainage and distribution were maintained and mostly developed. In France and Spain, agriculture seems to have been based on irrigation of small areas, exploited following agro-forestry models, from the Roman period to the Islamic and Christian periods (15th century in Spain) [14]. According to this scheme, the coltura promiscua is a mixed agricultural system attested in Medieval Italy (12–13th centuries). It is structured into three vertical levels: (1) crops, (2) being able to grow directly on fruit trees (e.g. grape vine), and (3) other trees such as Fraxinus sp. and Ulmus minor.

In the Western Mediterranean Basin, the ‘oulie`re’ cultivation system associating cereals and pulses, fruit trees (olive tree, white mulberry — Morus alba, grape vine — Vitis vinifera and other Rosaceae: Maloideae and Prunoideae), farming and grazing activities, may be considered as an inheritance of the Roman and Medieval agricultural models.

Archaeological (basins, canals and dams for water storage and distribution) and text documents (Roman and Medieval agronomic documentation) on the use and development of irrigation are sparse except in the Al-Andalus (Islamic Spain during the Middle Age) [2,12]. However, biological remains such as charcoal are found abundantly in Medieval sites. This is why, it was interesting to develop a bio-archaeological approach based on both modern and archaeological material. In this perspective, the approach developed and presented in this paper consists of studying the influence of irrigation on the anatomy of olive. It aims to contribute to a better understanding of cultivated plant biology and knowledge of the history of agriculture.

2. Material

Wood samples for the modern reference collection were taken from 20 different localities (Fig. 1), situated all over the Western Mediterranean Basin, except the Greek station. Special attention was paid to the Spanish Levante region, a very diversified region from an ecological point of view. This is why seven different locations were sampled in this region alone.

Wood was collected at different tree heights so that intra-tree variability of wood can be taken into account. This sampling protocol has provided numerous samples from wild olive trees growing in natural conditions, wild olive trees growing in riparian habitats, cultivated olives growing in dry conditions and irrigated cultivated trees. These trees are irrigated with ancient and traditional methods such as flooding of the bottom of trunk or of the orchard as a whole.

All of these samples were dried during several days and charred in a furnace under controlled anaerobic and thermal (400–450 °C) conditions. As a result, samples have reached their maximal size shrinkage and carbon enrichment and are thus comparable to charcoal produced in ancient fireplaces.

The archaeological material came from four Medieval sites (Fig. 1, Table 1): Lunel-Viel (Languedoc, France: 9–11th centuries), Cabrera d’Anoia (Cataluña, Spain: 11–beginning of the 14th century), Tarragona (Catalonia, Spain: 14th century) and Ortolo (Corsica, France: 15th century).

3. Methods

The quantitative eco-anatomical analyses carried out on charred samples from the reference collection and on charcoal fragments from the four Medieval sites were based on the methodological and analytical protocol developed previously by Terral and Arnold-Simard [23] and Terral [21]. Wood anatomy of charred wood fragments is observed with the assistance of a light-reflected compound microscope coupled with an analysis system (image acquisition and treatment). Measurement of anatomical features observed in transverse sections of manually fractured samples follows a radial line and cross several growth rings. Olive wood is characterised for being diffuse—porous with numerous vessels, isolated or grouped in radial lines of 2–5/7 (rarely up to even 15); rays are uniseriate, and

Fig. 1. Location of modern olive populations and Medieval archaeological sites from which study material came from.
parenchyma is paratracheal, i.e. parenchyma cells connected directly to vessel elements.

For each sample, several measurements were necessary in order to obtain a good and reliable estimation of each character, as previously shown by Terral [21]. The measured anatomical criteria are (1) ‘growth ring width’ (GRW, μm), (2) ‘vessel surface’ (SVS, μm²), (3) ‘vessel density’ (DVS, N/mm²), (4) ‘number of vessel per group’ (NVS). Finally, the hydraulic conductivity of vessels (CD) was calculated (CD = [vessel surface/mm²]/vessel density) [3,28].

However, although distinct growth rings are shown in the case of immature wood from young branches and twigs, these latest features become undistinguishable in mature wood from old branches and trunk [5,22]. This is why we have restricted our analyses on 446 samples from immature wood: 241 from wild olive trees growing in natural conditions, 45 from wild olive trees growing in riparian habitats, 114 from cultivated olives growing in dry conditions and 46 from irrigated cultivated trees.

For several archaeological fragments, it was also impossible to observe any growth rings. As a result, ‘growth ring width’ was not measured in all the samples. For other specimens, reduced dimensions and bad preservation explain our incapability to observe growth rings. These latest charcoal fragments were not taken into consideration.

Data from quantitative eco-anatomical analyses were treated by two distinct Canonical Variate Analyses (CVA). Associated to these multivariate statistical analyses, measurement data were applied to the Mann—Whitney non-parametric test (U-test) for detecting any effect of water on wild and cultivated olive wood anatomy. The choice of this test rather than the analysis of variance (ANOVA) is justified by the fact that olive groups are constituted by samples from distinct populations. In this case, the U-test is not dependant on the distributional assumptions of ANOVA [20].

The first CVA was carried out on 446 samples of modern charred wood and six variables (five quantitative anatomical characters and one qualitative variable expressing four modalities corresponding to the four olive groups). This analysis was undertaken in the hope of providing evidence of discriminate criteria between populations and to pinpoint links between the four statistical groups and the explanatory anatomical variables. Archaeological specimens with distinct growth rings were compared to the reference samples as additional individuals. They were brought into the multivariate statistical analysis to be assigned to a precise group.

The second CVA was carried out on the 446 modern samples and only five variables (the quantitative anatomical characters except ‘growth ring width’ and one qualitative defining the four olive groups). This second statistical analysis attempted to allocate the archaeological charcoal with indistinct growth rings to a specific olive tree group.

## 4. Results

Measurement data for modern olive wood samples treated by two different Canonical Variate Analyses (CVA) are summarized in Table 2.

### 4.1. Statistical analyses

The discriminate power computed by the first CVA is equal to 93.4%. Canonical scores 1 (CS1) of the first CVA based on all anatomical characters (expressing 57.2% of the total variance of individuals explained in the multi-dimensional space) discriminates between olive tree wood under water influence and olive trees growing in dry conditions (Fig. 2a). The significant variables contributing to the discrimination between these two groups are ‘vessel surface area’ and ‘conductivity’, two strongly correlated variables (see also results of associated tests presented in Table 3). Canonical scores 2 (CS2) (36.2% of variance explained) distinguishes wild olive growing in natural conditions characterised by narrow growth rings from wild olive growing in riparian conditions.

The second CVA in which ‘growth ring width’ was not included, discriminates 76.1% of olive samples. While the discriminating power of this statistical analysis is less efficient than the first CVA, it appears that three olive groups are...
well discriminated (Fig. 2b). Canonical scores 1 (CS1, explaining 81.9% of total variance) distinguishes olive trees (wild and cultivated) growing with an abundant water supply from a group including wild and cultivated trees growing in dry conditions. Canonical scores 2 (CS2, explaining 13.1% of total variance) separates riparian wild olive trees from the irrigated cultivated ones.

Other results unsupported by CV A were shown by Mann–Whitney non-parametric test. Although the accuracy of this test was clearly demonstrated previously [20], we prefer to consider and discuss only the highly significant results. Afterwards, divergences in ‘number of vessel per group (NVS)’ and in ‘density of vessel (DVS)’ were observed as a response of wood anatomy to water availability. For wild specimens, NVS appears to be higher for trees growing in riparian conditions than for specimens belonging to dry habitats (Table 3). Moreover, increasing values of DVS are noticed going from trees cultivated in dry conditions to irrigated ones.

4.2. Allocation of archaeological samples

Fig. 3 and Table 4 present the allocation of archaeological charcoal to olive tree groups defined on the basis of results from the two Canonical Variate Analyses carried out on eco-anatomical data. The majority of identified charcoal specimens are of the cultivated type. Some samples belong to the wild group, but we do not know if they correspond to native wild olive trees or feral forms. Among the cultivated specimens, many are allocated to irrigated individuals. These results seem to demonstrate that, in north-western Mediterranean areas, irrigation of olive trees was a practise employed during the Middle Ages. It should be noted that a substantial number of samples were not classified according to a specific group as they present intermediate anatomical characteristics.

5. Discussion

The wild olive tree is well adapted to the Mediterranean climate. In areas submitted to stressful summer conditions, it grows generally on well-drained limestone soils, in bush named garrigue in France and matorral in Iberian Peninsula. In semi-arid areas, such as in Southern Spain and Northern Africa, wild olive trees may be observed in riparian conditions, growing on banks of ephemeral rivers. This atypical ecological location offers trees a substantial water supply during the spring, period of maximum plant growth and development. In the summer, streams dry out and, under the new stressful conditions, tree growth stops.

Cultivated olive trees grow larger and faster than wild forms [23]. Even when they are cultivated without any irrigation system, favourable growing conditions achieved via adequate spacing, pruning and fertilization explain differences in growth. However, the driest regions are dependant on

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**Table 3**

Results of testing the effect of water on wood anatomy from both wild and cultivated olive trees using the Mann–Whitney non-parametric test.

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Anatomical criteria</th>
<th>U-test</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild − dry × wild − riparian</td>
<td>GRW</td>
<td>4656</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>SVS</td>
<td>7</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td></td>
<td>NVS</td>
<td>3216</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td></td>
<td>DVS</td>
<td>4295</td>
<td>0.03*</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>386</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td>Cultivated − dry × cultivated irrigated</td>
<td>GRW</td>
<td>1887.5</td>
<td>0.01*</td>
</tr>
<tr>
<td></td>
<td>SVS</td>
<td>13</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td></td>
<td>NVS</td>
<td>2081</td>
<td>0.04*</td>
</tr>
<tr>
<td></td>
<td>DVS</td>
<td>1355.5</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td></td>
<td>CD</td>
<td>26</td>
<td>&lt;0.001**</td>
</tr>
</tbody>
</table>

*Significant; **highly significant.
Fig. 3. Canonical Variate Analysis (CVA) biplots showing the allocation of archaeological samples from Lunel-Viel (top), Ortolo (middle), Tarragona and Carbrera d’Anoia (bottom) to a defined olive group. (a) CVA carried out on GRW, SVS, NVS, DVS and CD; (b) CVA carried out on SVS, NVS, DVS and CD. The dotted lines correspond to the four discriminated groups.
irrigation to guarantee an agricultural production [13]. In areas where more favourable climatic conditions do not require irrigation, this practise may be employed to increase productivity and quality of production [16].

From the anatomical point of view, a significant relation between wood characteristics and soil water availability was shown for both wild and cultivated olive. Hydraulic conductivity, linked directly to vessel surface increases strongly in response to water supply. It appears to be evident that high values of vessel surface area and of hydraulic conductivity calculated for both wild and cultivated olive, can be interpreted as an adaptation and an eco-physiological response of wood to water availability. These changes correspond to a greater efficiency of sap transport through xylem vessels (conductance).

Moreover, moisture appears to have a great influence on cambial activity for cultivated olive. It was indeed stated that water availability versus water stress reinforces cambium activity through an increase of cell turgor and cell enlargement [27]. A growth increase was evidenced by our results for irrigated cultivated olive when compared to cultivated olive growing in dry conditions (Table 3). On the other hand, wild olive trees show no difference in growth ring width between specimens growing in dry conditions and specimens growing in riparian habitats. However, concerning these two last groups, divergences in ‘number of vessel per group’ and ‘vessel density’ do not seem to be correlated to water. It has been previously reported that these two anatomical criteria are representative of cavitation vulnerability (air trapped in vessels involving deactivation of xylem conduction) [3,4]. This corresponds to the degree of security of sap conduction established by the plant and is strongly correlated to the bioclimatic conditions defined by thermo-climatic parameters [23,24]. High vessel density characterizing irrigated cultivated olive trees seems to match a higher stage of security. In case some vessels are deactivated by gaseous embolism, neighbouring vessels may take over. These olive trees (Greece, Southern Spain, Tunisia) growing under thermo-Mediterranean conditions and thus requiring high security have set up such quantitative anatomy.

The comparison of data from Medieval charcoal and the eco-anatomical model established based on living trees shows the existence of irrigation likely since the Carolingian period (9–10th centuries) in Languedoc (France). The use of irrigation is also sporadically referred to in charts and cartularies [6] and, in more detail, in agricultural house boundary treatises. In this case, information is very accurate, both from a technical and from a practical point of view, but we do not know if they were really applied by peasants. Advice concerning the whole fruit trees and recommendations on specific species such as olive tree remain exceptional. For example, P. de Crescenzi, agronomist living in Bologna (Italy) during the 13th century suggested the use of rain or cistern water to irrigate olive tree plantations instead of running water (Crescenzi in Ref. [19]). Ibn Al’-Awwâm, a famous Islamic agronomist of the 12th century proposed to sprinkle lately grafted olive trees (Al’-Awwâm in Ref. [7]).

Archaeological surveys and diagnoses have uncovered pits of plantations interpreted as Roman vineyards or orchards [1,9,15]. The first attestations of olive tree plantations were recently discovered in the Roussillon region, in Southern France [18]. Nearby pits of plantation, these parcels contain ditches and other ancient structures in hollow. It is possible that these structures might have been used for irrigation, but conclusive proofs are not available yet. Written documents and archaeological findings only provide indices on irrigation practises during the Middle Ages. When confronted with bio-archaeological results these indices have to be re-read and re-interpreted.

### 6. Conclusion

In short, the overall pattern of anatomical variability related to water availability seems to correspond to changes in vessel surface and hydraulic conductivity. Differences may be interpreted as physiological responses to environmental factors affecting sap flow, in preventing water loss by evapo-transpiration [10,11,25]. Thus, it is possible that these eco-anatomical criteria may follow predictable patterns such as the relation between conductivity and mean annual precipitation, as already modelled for the wild olive trees [24].

Wood anatomy patterns measured in this study, and applied to Medieval charcoal in an interdisciplinary bio-archaeological approach, have demonstrated for the first time the existence and importance of olive tree irrigation. This study constitutes the first steps towards a more representative and more exhaustive analysis in biological, agronomic and historical perspectives of the modes of irrigation and their influence on the anatomy of the wood of olive tree.
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