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Forest and agricultural dynamics in the Haouz plain over the last millennium: archaeobotanical and isotopic research at Aghmat (Morocco)

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Abstract

Over the last millennium, the town of Aghmat (Morocco) has undergone major socio-economic changes, raising the question of how these transformations have affected the development of agricultural systems and exploited landscapes over time. This preliminary pilot study brings together for the first time carpological, anthracological, and isotopic results from the Aghmat archaeological program that show a certain stability for staple productions (cereals, fruit) over the last millennium, and the exploitation of various landscapes. A shift appears to occur during the late Middle Ages, potentially due to more favorable conditions, with a specialization in olive cultivation as early as the fourteenth century, and significant deforestation following this olive growing boom. During the modern period, the importance of olive cultivation is confirmed, whether or not in conjunction with a decline in water availability and what appears to be irreversible deforestation.

Keywords

Medieval period; Muslim agriculture; Irrigation; Crop Fertilization; Archaeobotany; Stable isotopes; Water Use Efficiency; Olive Cultivation; Aghmat; Morocco

Introduction

42 Numerous studies over the last several decades have addressed the relationship between
43 human societies and their environments (both agricultural and forestry) in the medieval and
44 modern western Mediterranean using written and iconographic sources (e.g., Bourin-derrau,
45 1987), archaeological sources (e.g., Demians d'Archimbaud, 1982), or a combination of
46 several of these sources (e.g. Ouerfelli & Voguet, 2009). With rare exceptions (e.g., Durand,
47 1998; Puig, 2003; Ros et al., 2014), this extremely rich body of work has focused on the
48 occupation of the countryside in the broadest sense (occupation dynamics, land structuring),
49 without specifically focusing on characterizing the exploited plant resources, cultivation
50 practices (manure, irrigation), or agrosilvopastoral landscapes, which are fundamental to
51 establishing how past societies adapted their methods of exploiting plants and animals, and
52 the landscapes in which they evolved, according to the socio-economic (local, global) and
53 environmental context (climate change, availability of resources). The study of agricultural
54 and forestry systems is particularly interesting over the long term as it provides the necessary
55 hindsight to understand their evolution, their resilience, and the role of each parameter
56 (cultural, economic, political, environmental) that has influenced them.

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58 The development of archaeobotany in the 1970s and 1980s in France and Spain led to
59 the production of the first synthesis documenting, on a local or regional scale, the agricultural
60 and forestry systems of the historic western Mediterranean (e.g., Durand, 1998; Ruas, 2005;
61 Peña-Chocarro et al., 2019; Ros et al., 2019; Ros, 2020). In Morocco, these systems have long
62 been studied solely through the prism of textual sources, in particular works by geographers
63 and travel accounts. Over the same decades, several archaeological missions have initiated
64 research into medieval agrosilvopastoral production, practices, and landscapes, resulting in a
65 number of pioneering publications (Pollock, 1986), although several studies remained
66 unpublished and difficult to access. The 2000s saw a new development (Ruas, 2018) resulting
67 from interdisciplinary approaches in ancient and medieval sites, such as Lixus and Volubilis
68 (Grau Almero et al., 2001, 2010; Fuller, 2002, 2004; Pérez Jordà, 2005; Fuller & Stevens,
69 2009; Fuller & Pelling, 2018). Since the 2010s, new sites have been and are still being
70 investigated on a large scale, with research dedicated to the palaeoenvironmental
71 reconstructions. Examples include the large-scale excavations at Îgîlîz, Rirha, and Thamusida
72 (Ruas et al., 2011, Allevato et al., 2013, 2016; Ruas et al., 2016a, b; Carrato et al., 2020).
73 Among these regions, Al Haouz has been the focus of particularly important archaeological,
74 bioarchaeological and ethnological research in recent years, particularly in the area of
75 Aghmat, a town of medieval origin located at the foot of the High Atlas (Ros et al., 2021),

76 because of its chronology of occupation, which spans the whole of the High and Late Middle
77 Ages, and part of the Modern era.

78

79 ***Aghmat: Environmental and archaeological context***

80 The city of Aghmat is located about 35 km south-southeast of Marrakesh (Morocco) at an
81 altitude of about 541 m.a.s.l. in the high altitude plain of the Haouz, at the foot of the High
82 Atlas Mountains (Ait El Mekki & Laftouhi, 2016) (Fig. 1). According to Héritier-Salama et
83 al. (2016), its location on the plain at the mouth of the Ourika valley was highly conducive to
84 the early development of large-scale irrigated agriculture. It has a warm, semi-arid climate
85 (BSh climate type according to Koppen climate classification, Koppen 1936), the minimal
86 and maximal mean temperatures ranging from 10.9°C to 24.8°C (AQUASTAT Climate
87 Information Tool, FAO; <http://www.fao.org/nr/water/aquastat/climateinfotool/index.stm>). The
88 annual average precipitation is 541 mm/year (Saidi et al., 2010). The soil, with modern
89 Quaternary formations, is Fersiallitic (medium Sandy Clay Loam) of good permeability and
90 drainage (i.e., gravel, sand) (Ait El Mekki & Laftouhi, 2016). These climatic and
91 environmental conditions allow the development of the *Quercetea ilicis*, an often evergreen
92 and sclerophyllous Mediterranean shrub/tree vegetation (Achhal, 1979; Barbéro & Quézel,
93 1981; Benabid, 1982). Groups of araar trees (*Tetraclinis articulata*) are found on the foothills
94 of the Atlas mixed with other species (*Juniperus phoenicea*, *J. oxycedrus*, *Pistacia lentiscus*,
95 *Cistus monspeliensis*, and, on shady slopes, with *Quercus ilex* subsp. *rotundifolia*, *Arbutus*
96 *unedo*, *Phillyrea angustifolia*, *Cistus salviifolius*) (Benabid, 1985; Fennane, 1988; Ouhammou
97 & Aubin, 1991). Further downstream from Aghmat a thermophilous shrubland develops
98 (*Pistacia lentiscus*, *Ziziphus lotus*, wild *Olea europaea*) (Quézel & Médail, 2003). The fertile
99 Ourika valley allows cultivation of cereal and tree crops (Héritier-Salama, 2019).

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Fig. 1: Location of the archaeological site of Aghmat and aerial view of the site (in the photo on the right, the white area corresponds to the current village and the dotted area to the entire archaeological site).

During the Middle Ages, Aghmat is described by textual sources at the beginning of the ninth century as "a major commercial crossroads, a flourishing city and a very important agricultural production centre." It became a capital under the Almoravids in 1058, but was then gradually abandoned towards the end of the fourteenth century in the face of the hegemony of the new Almoravid capital: Marrakech. In the sixteenth century, Leon the African described a ruined city occupied by rural inhabitants. Since 2005, archaeological studies of Aghmat have allowed a better understanding of this transitional period during the Late Middle Ages (fourteenth-fifteenth centuries) (Fig. 2). The archaeological data show that the period of abandonment was very gradual, over nearly two centuries from the fourteenth to the end of the fifteenth, and partial, never really leading to a total desertion, with certain districts being reinhabited or changing function (Héritier et al., 2016). The sixteenth century was characterized by the arrival of a more rural and modest population, the Sufis, a brotherhood of ascetics (Héritier et al., 2016). Aghmat also saw immigration linked to the Portuguese incursions on the coast. The town then underwent a settlement breakdown and an agricultural conversion (Héritier et al., 2016). While these major socio-economic dynamics are becoming well understood from a historical and archaeological point of view, their possible effects on landscapes use and on agropastoral productions and practices are only beginning to be explored (Ros et al., 2021). Consequently, we propose a preliminary pilot study that demonstrates the great value of combining different methods and materials.



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Fig. 2: Location map of the different archaeological areas excavated by the Mission Archéologique d'Aghmat (state at the end of the 2019 campaign): the architectural remains are those which have been abandoned at the end of the 14th century as the urban occupation phase of the settlement was coming to an end (Document: Mission Archéologique d'Aghmat).

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Research Goals

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- Reconstruct the diversity and evolution of the forest cover over the last millennium in relation to changes in the city's status
- Document the main cultivated/exploited plant species and any changes they may have undergone (diversity, type of remains, frequency)
- Highlight agricultural practices (fertilization, irrigation, land used) in relation to cereal growing.

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Materials and methods

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Origin of the archaeobotanical samples and method of extraction and identification

144 We analyzed a total of 26 archaeobotanical samples from 23 archaeological features. These
 145 features mainly correspond to secondary deposits from ‘open’ features, such as ditches, living
 146 spaces (e.g., houses), gardens, rubbish dumps, plantation pits and hearths. The original
 147 volume of the samples ranges from 0.5 to 14 liters. All the samples were sieved using a
 148 flotation machine (2 mm and 250 μm) during the different excavation campaigns.

149 The identification of the seed and charcoal remains was carried out at the ISEM
 150 laboratory (Montpellier, France), using a Nikon SMZ645 stereoscopic magnifier (x0.8 to x10
 151 magnification). For the identification of seed remains, we used a reference collection of fresh
 152 and archaeological seeds as well as Cappers et al., 2006; Jacomet, 2006; Rameau et al., 2008.
 153 The remains were quantified, either as entire specimens or as fragments and the frequency of
 154 occurrence of cultivated taxa was calculated per sample / phase. For anthracological analysis,
 155 specific recognition was done using an Olympus BH2-UMA reflection microscope, with
 156 black/white background and x100, x200 and x500 magnification, with the help of reference
 157 atlases (Jacquiot, 1955; Jacquiot et al., 1973; Schweingruber, 1990; Vernet et al., 2001) and
 158 the reference collection of the team "Dynamique de la biodiversité, anthropo-écologie"
 159 (ISEM, UMR 5554). The latin nomenclature follows the French ‘Inventaire National du
 160 Patrimoine Naturel’ (Museum National d’Histoire Naturelle, Paris).

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162 *Radiocarbon datings*

163 Radiocarbon age determinations were performed on eight charred seeds (naked wheat and
 164 barley caryopses, olive kernel, jujube kernel fragment) extracted from eight different
 165 stratigraphic units, using AMS (Accelerator Mass Spectrometry) facilities at Poznan
 166 Radiocarbon Laboratory (Table 1). The calibration of ^{14}C -dates was performed using OxCal
 167 4.4 program version and the calibration data set was IntCal20 Northern Hemisphere
 168 atmospheric curve (Reimer et al., 2020) (Table 1).

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Sample name	Lab. No	Age 14C (BP) and error		Age range, Cal AD (2 σ) 99.6% probability		^{14}C Cal BP Mean 2 σ		^{14}C Cal BP Median 2 σ
		930	30	1026	1217	1107	44	1104
AGH4204	Poz-135619	930	30	1026	1217	1107	44	1104
AGH1561	Poz-135847	800	30	1166	1283	1242	21	1244
AGH2361	Poz-135647	645	30	1278	1402	1342	35	1353
AGH4327	Poz-135633	625	30	1281	1409	1346	32	1350
AGH2032	Poz-135645	590	30	1293	1425	1354	31	1348
AGH2419	Poz-135649	560	30	1300	1440	1371	36	1361
AGH2438	Poz-135648	530	30	1307	1450	1401	32	1412
AGH1523	Poz-135968	525	30	1312	1452	1406	30	1414

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171 Table 1: Radiocarbon dating on 8 charred seeds (naked wheat and barley caryopses, olive kernel, jujube kernel
 172 fragment) extracted from 8 different stratigraphic units, using AMS (Accelerator Mass Spectrometry) facilities at
 173

Poznan Radiocarbon Laboratory

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175 *Isotopic analysis*

176 A total of 40 archaeobotanical charred seeds of hulled barley (n=20) and naked wheat (n=20)
 177 were selected for carbon, nitrogen and sulfur isotopic analysis ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{34}\text{S}$). All were
 178 rinsed three times for 10 min in ultrapure Milli-Q® water at room temperature, dried
 179 overnight (40°C), before being crushed and homogenized. About 0.5 to 2 mg of powder was
 180 then weighed using a precise balance ($\pm 1 \mu\text{g}$) and loaded into small tin capsules (3.5 x 5 mm)
 181 for N and C. For sulfur, 10 to 15 mg of material were introduced in bigger tin capsules (5 x 8
 182 mm size). The crushing and encapsulation were carried out using tweezers that were cleaned
 183 between each sample.

184 Isotopic and elemental contents analysis for C, N and S were measured by dry
 185 combustion using a Pyrocube Elemental Analyser (EA, Elementar GmbH) equipped with a
 186 purge and trap gas separation system configured in combustion mode (Fourel et al., 2014).
 187 The elemental Analyser was connected on line in continuous flow mode to an IsoPrime 100
 188 isotope ratio mass spectrometer (Elementar UK Ltd). Data were calibrated against
 189 international reference material IAEA-600, IAEA-CH6 and IAEA-N2. The $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and
 190 $\delta^{34}\text{S}$ values are expressed in δ notation, deviation from standards in parts per thousand (‰),
 191 relative to V-PDB (Vienna Pee Dee Bee Belemnite), V-N2 (atmospheric N₂) and V-CDT
 192 (Vienna-Cañon Diablo Troilite) respectively: $\delta^m\text{X} = (\text{R}_{\text{sample}}/\text{R}_{\text{standard}} - 1) \times 1000$ where R =
 193 $^{13}\text{C}/^{12}\text{C}$ for carbon, $^{15}\text{N}/^{14}\text{N}$ for nitrogen or $^{34}\text{S}/^{32}\text{S}$ for sulfur. The precision for $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and
 194 $\delta^{34}\text{S}$ is better than 0.1 ‰. The results of elemental C, N, S contents are expressed as (%) and
 195 are also presented as C/N and N/S atomic ratios.

196 Correction factors are applied to the $\delta^{13}\text{C}$ seed samples due to long term changes of
 197 the carbon isotopic composition of the atmospheric CO₂ ($\delta^{13}\text{C}_{\text{AIR-CO}_2}$) over time according to
 198 Antarctic ice core records (Francey et al., 1999; Leuenberger et al., 1992), as described in
 199 Ferrio et al. (2005). $\delta^{13}\text{C}$ seed values and $\delta^{15}\text{N}$ seed values were also corrected for the effect
 200 of charring (+0.11‰ for the $\delta^{13}\text{C}$ and +0.31‰ for the $\delta^{15}\text{N}$; Nitsch et al., 2015). During
 201 biological processes, isotopic differences (*i.e.* between tissues, species) can be calculated and
 202 those represented by the “ Δ ” symbol corresponds to isotopic discrimination. We calculated
 203 the carbon isotopic discrimination ($\Delta^{13}\text{C}_{\text{SEED-CO}_2}$) by adapting the equation of Farquhar et al.
 204 (1982), $\Delta^{13}\text{C}_{\text{SEED-CO}_2} = (\delta^{13}\text{C}_{\text{AIR}} - \delta^{13}\text{C}_{\text{SEED}}) / (1 + \delta^{13}\text{C}_{\text{SEED}}/1000)$, where $\delta^{13}\text{C}_{\text{AIR}}$ and $\delta^{13}\text{C}_{\text{SEED}}$
 205 refer to the $\delta^{13}\text{C}$ of the atmospheric CO₂ and $\delta^{13}\text{C}$ of the plant, respectively. In C3 plants,
 206 carbon isotopic composition is determined by the diffusive discrimination of ^{13}C in air
 207 through the stomata (4.4‰), the net discrimination caused by carboxylation through the

208 RuBisco enzymatic activity (29 ‰) and by the ratio of intercellular (ci) to ambient (ca) leaf
209 partial pressures of CO₂ (Farquhar et al., 1989; Maxwell et al., 2018).

210 Charred seed $\Delta^{13}C$ were compared with the reference threshold $\Delta^{13}C$ values that
211 differentiate between plant growth under well-watered and drier conditions. We used the
212 reference threshold $\Delta^{13}C$ values of 17.0 to 18.5 ‰ for moderately watered barley and 16.0 to
213 17.0 for moderately watered wheat (Araus et al., 1997; Wallace et al., 2013).

214 Using the $\Delta^{13}C_{SEED-CO_2}$, we assessed the water use efficiency (WUE_i expressed in
215 $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$) as leaf net photosynthesis (A) is related to the leaf conductance of the
216 water vapor (gH₂O) as described in Du et al., (2021): $WUE_i = (b - \Delta^{13}C_{SEED-CO_2}) / 1.6 * (b - a)$,
217 where a is 4.4‰ and b is 27‰. We also evaluated the water input during cereal filling
218 (expressed in mm) using the model described for wheat (*Triticum aestivum*) and barley
219 (*Hordeum vulgare*) in the South-West Mediterranean region (Araus et al., 1997; Ferrio et al.,
220 2004, 2005; Speciale et al., 2020).

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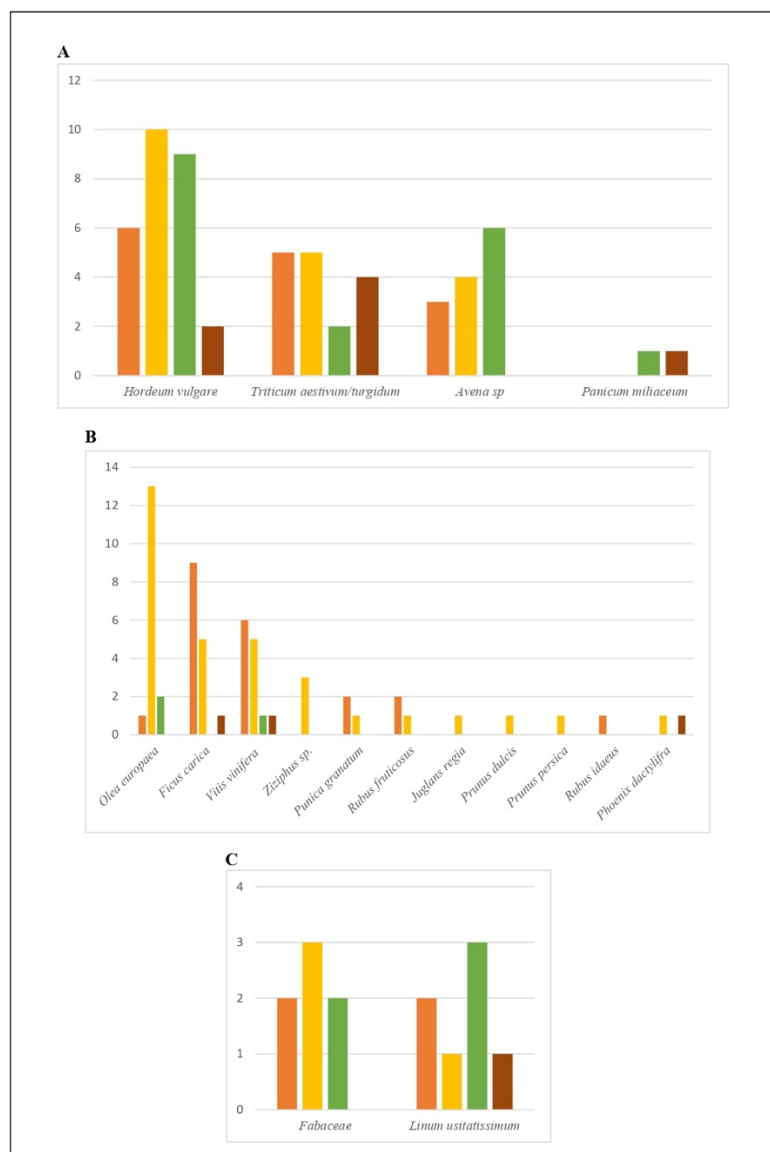
222 **Results**

223 ***Seed remains***

224 Of the 26 available samples, 21 were fully sorted, identified and quantified; the remaining six
225 samples were surveyed, i.e., their taxonomic diversity was recorded and their abundance
226 assessed. We studied a total of 7545 carpological remains preserved by carbonization, of
227 which were identified 7473 (see Appendix 1 for raw data).

228 The plant taxonomic spectrum is made up of 60 taxa, classified into five categories:
229 cereals, legumes, technical/textile plants, fruit trees and wild plants. Cereals formed the most
230 abundant category of cultivated plants, with 2050 remains (27.4% of all the identified
231 remains) and also the second most frequent in the samples (present in 20 samples out of 26)
232 (Fig. 3). We recorded at least 6 cereals: hulled barley (*Hordeum vulgare*), naked wheat
233 (*Triticum aestivum/turgidum*), millet (*Panicum miliaceum*), oat (*Avena* sp.), a possible hulled
234 wheat (*Triticum* type *monococcum/dicoccum/spelta*) and potentially rye (cf. *Secale*). Among
235 the chaff remains, the presence of some well-preserved rachis suggests the presence of both
236 hexaploid and tetraploid wheats. Fruit trees were the most abundant cultivated plants, with
237 843 remains (11.3% of the identified remains, present in 21 samples out of 26) (Fig. 3). We
238 recorded 11 taxa: olive (*Olea europaea*), fig (*Ficus carica*), grapevine (*Vitis vinifera*), walnut
239 (*Juglans regia*), date palm (*Phoenix dactylifera*), almond (*Prunus dulcis*), peach (*Prunus*
240 *persica*), pomegranate (*Punica granatum*), blackberry (*Rubus fruticosus*), raspberry (*Rubus*

241 *idaeus*) and jujube (*Ziziphus* sp.). Most of these remains were food residues (seeds or pits
 242 without flesh). Pulses and technical/textile plants were fairly rare (Fig. 3). Pulses were only
 243 recorded by 25 remains (0.3% of total remains, present in seven samples), and their bad state
 244 of preservation did not allow them to be identified beyond the family, although a possible
 245 *Lathyrus* might have been present. Flax (*Linum usitatissimum*) was recorded by four seeds
 246 (0.1% of remains) in 4 samples, but was observed in two of the surveyed samples. Finally,
 247 wild plants were recorded by 4552 remains (60.9% of the total remains, present in 16
 248 samples), corresponding to 40 taxa, 13 of which were identified to species. Most of these wild
 249 plants came from a single sample (SUQ2363-north, fifteenth-sixteenth centuries).

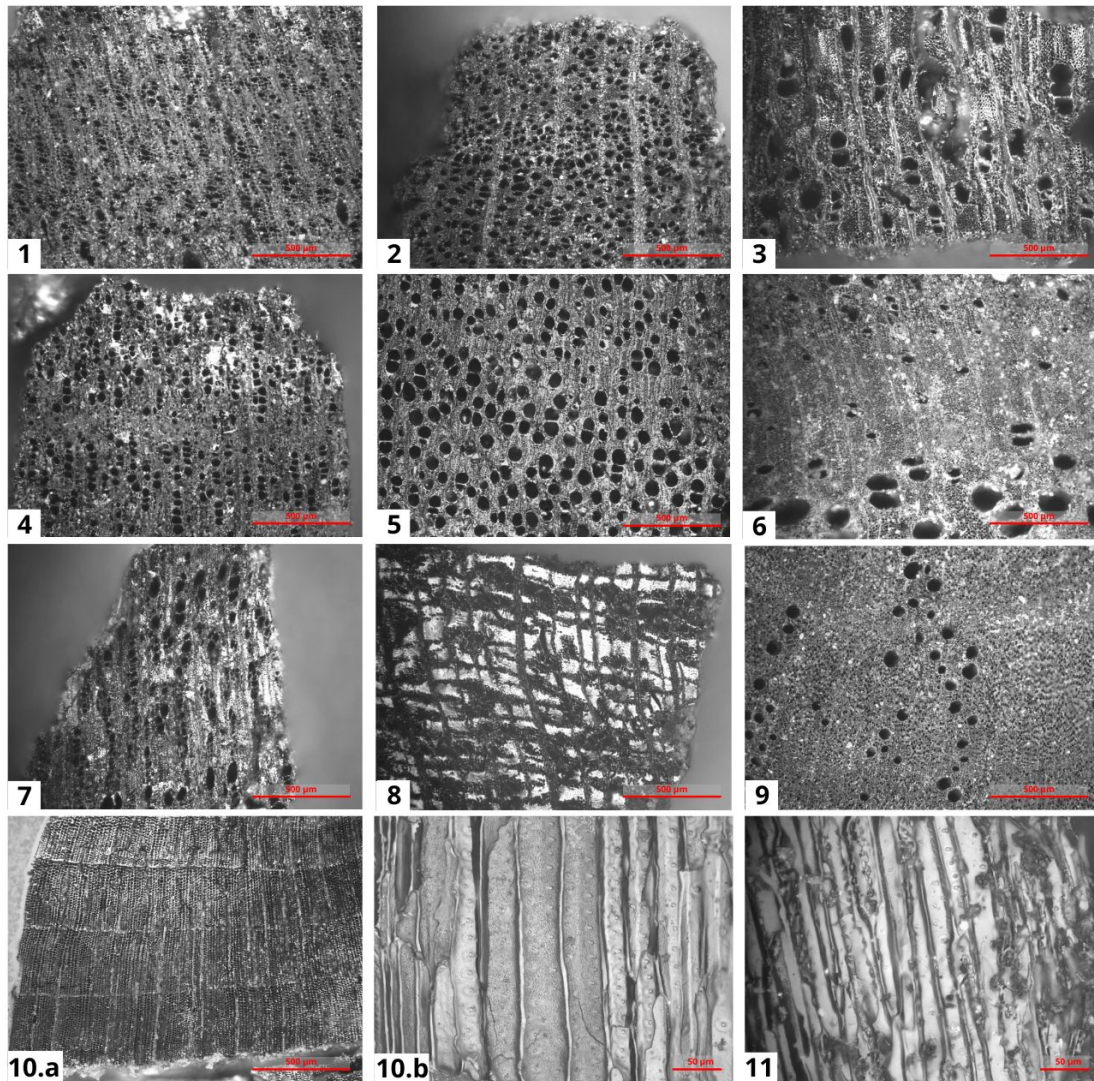


251 Fig. 3: Frequencies of carpological taxa (A: cereals; B: fruits; C: cultivated pulses and flax) for each phase (x
252 axis indicates the taxa; y axis indicates the number of contexts in which the taxa is recorded) (orange: 11th-12th
253 c.; yellow: 13th-14th; green: 15th-16th; brown: 17th-20th)

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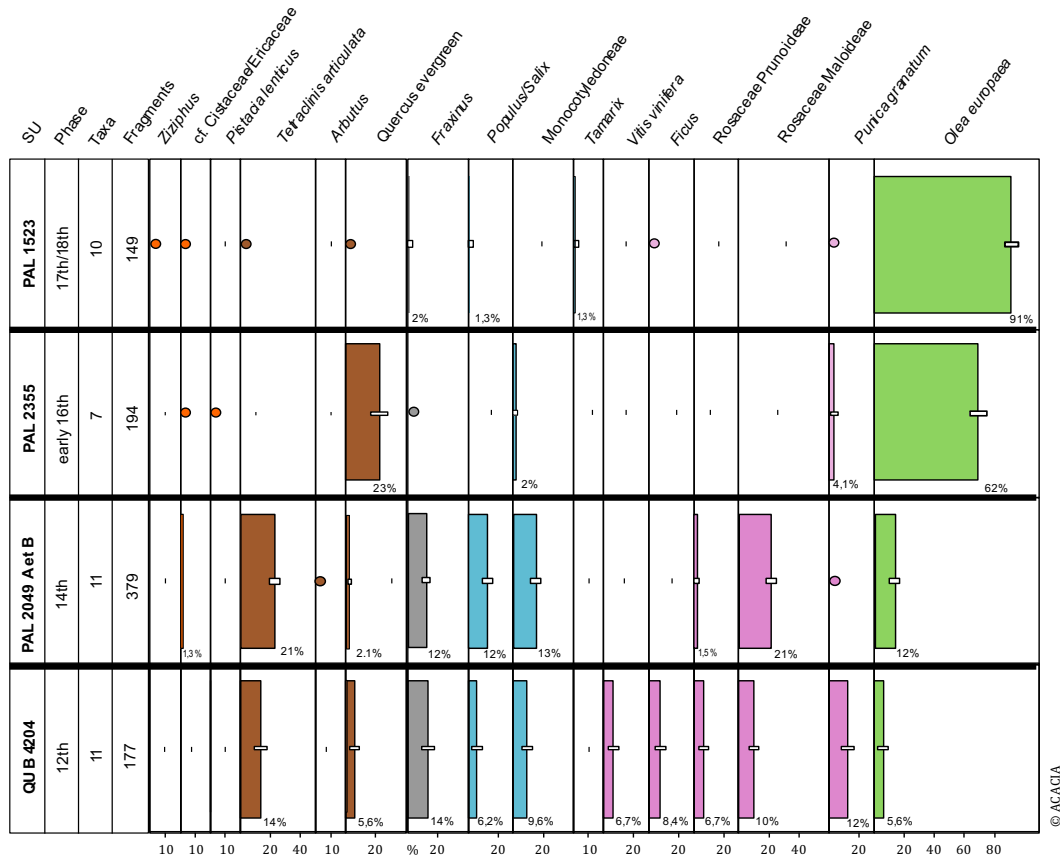
255 ***Charcoal remains***

256 Of all the available samples, eight yielded sufficient charcoal fragments to complete the
257 anthracological study. We studied a total of 1363 charcoal fragments, of which we identified
258 1301 at the family, genus or species level (see Appendix 2 for raw data). At least 17 different
259 taxa were identified, with the anthracological spectrum dominated by olive (*Olea europaea*),
260 which represented 36.5% of the studied charcoals, followed by evergreen oak (potentially
261 holm oak, *Quercus ilex* subsp. *rotundifolia*, established in this region), which accounts for
262 14.7% of the anthracological spectrum, and araar tree with 7.9% (*Tetraclinis articulata*).
263 Although junipers and the araar tree are very similar in anatomy, the latter was identified by
264 the presence of warts on its tracheids walls (Schweingruber, 1990: 145) (Fig. 4).
265 Approximately 9.8% of the fragments correspond to wadi edge species, i.e. 5.4% grass-type
266 monocotyledons, 4.3% poplar/willow (*Populus/Salix*) and 0.1% tamarisk (*Tamarix*). The
267 identification of ash (5.6%) is difficult to attribute ecologically, as there are two types of ash
268 in this part of Morocco: *Fraxinus angustifolia*, which is a riparian/wadi edge species, and
269 *Fraxinus dimorpha*, which is an endemic forest species found in association with *Quercus ilex*
270 on the High Atlas slopes. Fruit trees make up around 13.8% of the corpus, i.e., 7% Rosaceae
271 maloideae, 2.1% pomegranate (*Punica granatum*), 1.8% Rosaceae prunoideae, 1.3% fig
272 (*Ficus carica*) and 1% grapevine (*Vitis vinifera*). Among the prunoideae charcoals identified,
273 there is a diversity that is not due to intraspecific anatomical variation. On the tangential
274 longitudinal plane, some rays are one to three series while others have seven-eight series
275 (Appendix 2); the latter can be attributed to the *Prunus armeniaca/dulcis/persica* group, i.e.,
276 almond, apricot and peach. Next, 0.4% of pistachio trees (*Pistacia lentiscus*) and 0.7% of
277 potential pistachio trees (Anacardiaceae/cf. *Pistacia*) and finally, 0.3% of filaria/ buckthorn
278 (*Phillyrea/Rhamnus*), 0.2% of acacia/fig tree (*Acacia/Ficus*) and 0.1% for the following taxa:
279 strawberry tree (*Arbutus*), Cistaceae/Ericaceae, rockrose (*Cistus*) and jujube (*Ziziphus*). The
280 results for the SU that yielded the greatest number of identifiable charcoals were represented
281 in diagrammatic form (Fig. 5), showing the relative proportions of taxa exploited over time.



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283 Fig. 4: Anatomy of Aghmat's charcoal fragments. 1) Transverse plane of *Olea europaea*, 2) Transverse plane of
284 Rosaceae *Prunoideae*, 3) Transverse plane of *Ficus*, 4) Transverse plane of *Punica granatum*, 5) Transverse plane
285 of *Populus/Salix*, 6) Transverse plane of *Fraxinus*, 7) Transverse plane of *Pistacia*, 8) Transverse plane of
286 Fabaceae *Faboideae*, 9) Transverse plane of *Quercus* evergreen, 10. a) Transverse plane of *Tetraclinis articulata*,
287 b) Verrucose walls of *Tetraclinis articulata* in radial longitudinal plane, 11) Non-verrucose walls of *Juniperus* sp.
288 in radial longitudinal plane.



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Fig. 5: Diachronic anthracological diagram produced in Excel 2003 ACACIA macro (Nourissier *et al.*, 2016).

291

The species proportions are colored according to the vegetation assemblage to which they are assimilated:

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brown= oak/tetracline forest; grey= ash that may belong to the oak/tetracline forest or to the wadis banks;

293

blue=alluvial/riparian/wadis forest; pink=potentially cultivated taxa, green=olive tree.

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295 *Charred seeds isotopic compositions*

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The carbon, nitrogen and sulfur isotopic ratios of the studied taxa (*Hordeum vulgare*, *Triticum*

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aestivum/turgidum) for the period spanning the eleventh-twelfth through the seventeenth-

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twentieth centuries are presented in Appendix 3, as well as the details of the mean and

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standard deviation per periods. Over the 40 charred seeds selected for isotopic analyses, three

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of them did not provide enough gas for their isotopic analysis (below the detection limit of the

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mass spectrometer) and were not useful. Hence, we obtained 20 and 17 carbon isotopic

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records of barley and naked wheat, respectively.

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Naked wheat samples had $\delta^{15}\text{N}$ (n= 16) and $\delta^{13}\text{C}$ values (n=17) ranging from 3.3 to

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8.9 ‰ (mean value 6.0 ± 2.0 ‰), and from -23.6 to -21.1 ‰ (mean value -22.6 ± 0.7 ‰)

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respectively, and $\delta^{34}\text{S}$ (n = 9) ranging from 2.0 ‰ to 17.8 ‰ (mean value 10.8 ± 7.0 ‰). The

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mean values of C, N and S contents of the charred naked wheat seeds were on average $40.7 \pm$

307

12.3 %, 2.5 ± 1.0 % and 0.2 ± 0.1 % respectively. Hulled barley samples had $\delta^{15}\text{N}$ (n = 19)

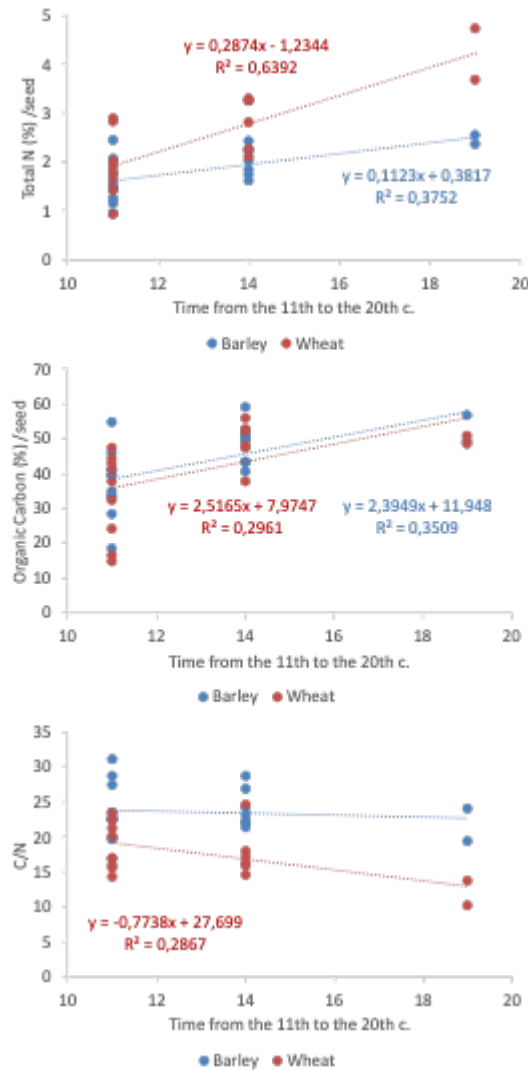
308 values ranging from 2.3 to 9.0 ‰ (mean value $5.6 \pm 1.9\%$) and $\delta^{13}\text{C}$ (n = 20) values ranging
309 from -24.9 to -21.6 ‰ (mean value $-23.3 \pm 0.8\%$), and $\delta^{34}\text{S}$ (n = 10) ranging from - 1.1 to
310 19.5 ‰ (mean value $12.5 \pm 7.9\%$). The mean values of C, N and S contents of the charred
311 hulled barley seeds were on average $43.1 \pm 10.2\%$, $1.8 \pm 0.5\%$ and $0.2 \pm 0.1\%$ respectively.

312

313 For the entire period, the WUEi, expressed in $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$, calculated for
314 barley and naked wheat ranged between 62.2 and 88.4 ($75.3 \pm 6.9 \mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$, n=
315 20) and between 73.8 and 94.0 ($80.9 \pm 6.0 \mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$, n= 17), respectively. Water
316 input during barley and wheat cereal filling ranged between 39.7 and 368.7 mm (144.1 ± 81.5
317 mm, n=20) and from 38.4 to 163.4 mm (102.8 ± 40.2 mm, n=17) respectively.

318

319 Carbon and nitrogen contents of the naked wheat charred seeds showed an increase
320 between the eleventh-twelfth through the seventeenth-twentieth centuries. The same trend was
321 observed for hulled barley, although the N content increase over time seems to be less
322 important (Fig. 6). C/N ratios ranged from 17 to 31 (24 ± 4) for barley and from 10 and 25 (18
323 ± 4) for naked wheat (Fig. 6).

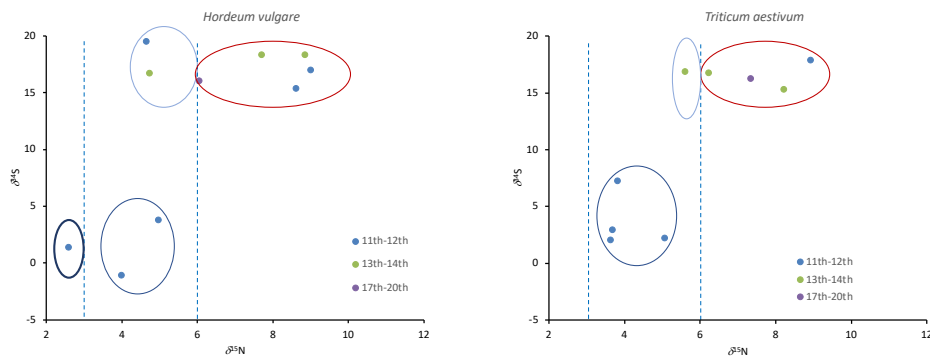


324
 325 Figure 6: Nitrogen, carbon and C/N ratios for the wheat (red bold circle) and barley (blue bold circles).
 326 The time axis is only indicative of the period spanning from the 11th to the 20th c.

327
 328 For each period, mean $\delta^{13}\text{C}$ values of naked wheat were always higher (-22.7 ‰ to -
 329 22.5 ‰) compared to hulled barley (-23.7 ‰ to -23.0 ‰), and showed smaller variations
 330 between the three periods. On the contrary, naked wheat mean $\delta^{15}\text{N}$ values showed higher
 331 variations from 5.4 ‰ (eleventh-twelfth centuries) to 8.0 ‰ (seventeenth-twentieth centuries
 332 17th-20th c.) compared to hulled barley (5.4 ‰ during the fourteenth -sixteenth centuries to 6.1
 333 ‰ for the seventeenth-twentieth centuries). For both naked wheat and hulled barley, $\delta^{34}\text{S}$
 334 showed two groups of values (below 7 ‰ and above 15 ‰, Appendix 3, Fig. 7) during the
 335 first period, but not during the two following periods, exhibiting only $\delta^{34}\text{S}$ values higher than
 336 15 ‰. The lowest reconstructed precipitation rate during cereal filling derived from the
 337 nitrogen isotopes were calculated for both naked wheat and hulled barley for the 17th-20th c.
 338 (53 ± 22 mm and 92 ± 13 mm respectively), while the highest precipitation rate was found

339 during the eleventh-twelfth centuries both for naked wheat (133 ± 74 mm) and hulled barley
 340 (128 ± 81 mm), although the latter was very close to the mean value calculated for the
 341 fourteenth -sixteenth centuries (Appendix 3). The higher calculated annual precipitation using
 342 the $\Delta^{13}C$ of hulled barley were observed during the fourteenth -sixteenth centuries (190 ± 102
 343 mm or 142 ± 52 mm if we remove the two outliers JR 61 and JR 62 samples) and the lowest
 344 during the eleventh-twelfth centuries (109 ± 45 mm).

345



346

347 Figure 7: $\delta^{34}S$ values with respect to the $\delta^{15}N$ of hulled barley and naked wheat for the three studied periods.

348

349 We did not find isotopic differences between the different studied periods for naked
 350 wheat (Kruskal Wallis tests, $\delta^{13}C$: chi-squared = 1.2476, p-value = 0.583, $\delta^{15}N$: chi-squared
 351 = 2.4835, p-value = 0.345, $\delta^{34}S$: chi-squared = 2.2044, p-value = 0.413) and hulled barley
 352 (Kruskal Wallis tests, $\delta^{13}C$: chi-squared = 2.7036, p-value = 0.26, $\delta^{15}N$: chi-squared =
 353 1.0665, p-value = 0.616, $\delta^{34}S$: chi-squared = 2.2182, p-value = 0.437).

354

355 Discussion

356 To gain a detailed understanding of changes in the wooded and agricultural landscapes of the
 357 Haouz plain over the last millennium, we decided to structure the discussion chronologically,
 358 by cross-referencing the archaeobotanical and isotopic data available for each period. We
 359 discuss the isotopic values of the first period (eleventh-twelfth centuries) in detail compared
 360 to the other periods, as it presents the higher number of samples. It also seemed important to
 361 detail for this first period our interpretations of the $\delta^{15}N$, $\delta^{34}S$ and $\delta^{13}C$ in terms of the
 362 presence/absence of manure, the homogeneity/heterogeneity of the terroirs and the availability
 363 of water, allowing us to get straight to the point for the following periods.

364

365 *The golden age of Aghmat (eleventh-twelfth centuries)*

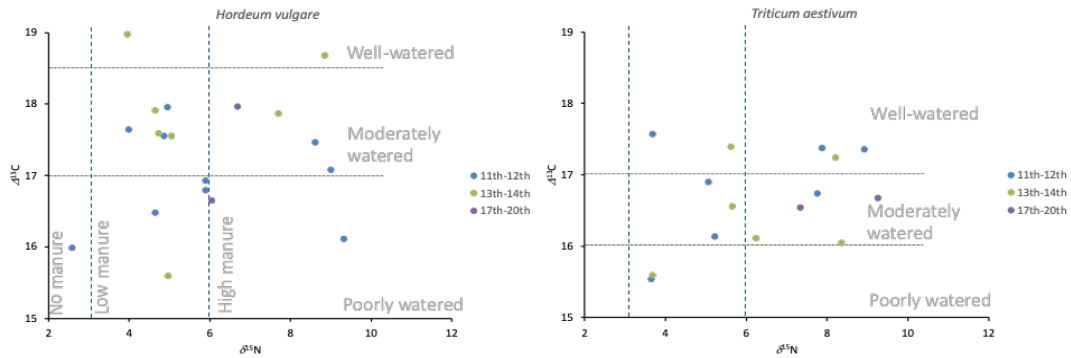
366 Founded around the tenth century, Aghmat underwent rapid development during the eleventh-
 367 twelfth centuries, experiencing strong economic growth. Samples from this period provide the
 368 earliest known archaeological evidence of the plant landscapes and productions of this region.
 369 At that time, the inhabitants of the site collected wood on the shaded slopes of the High Atlas
 370 (*Tetraclinis articulata*, *Quercus coccifera/ilex*, *Fraxinus*) and on the Ourika riverbanks
 371 (*Populus/Salix*, Monocotyledon) (Fig. 5). These woods account for half of the fuel, the other
 372 half being made up of a wide variety of fruit trees (*Vitis vinifera*, *Ficus*, *Punica granatum*,
 373 *Olea europaea*, *Rosaceae prunoideae*, *R. maloideae*). In textual sources, the recurrent
 374 description of abundant gardens, both on the outskirts of the city and within the city,
 375 underlines the importance of local horticulture and arboriculture (Al-Bakrî, 1911; Al-Idrîsî,
 376 1866). We can assume that the abundance of pruning waste generated by urban arboriculture
 377 meant that this wood was regularly available and reused as domestic fuel. Seed remains also
 378 confirm local consumption of these fruits, with figs and grapes being the most prevalent, as
 379 well as the production of olive oil. The latter is thought to have been small-scale, and intended
 380 for domestic consumption, given the absence of large production structures (olive presses).
 381 Other consumed plant species include hulled barley, naked wheat, large-seeded legumes, and
 382 flax, in other words a typical agrohorticultural diversity for Morocco at that time (Ruas 2018).
 383 The scarcity or absence of chaff and pod elements suggests that these were ready-to-eat
 384 elements, and it remains to be seen whether they were locally grown or imported.

385 This question can be addressed to some extent with the $\delta^{34}\text{S}$ of both barley and wheat,
 386 showing two distinct groups of values for both cereals, with mean values of $2.6 \pm 2.5\text{‰}$ ($n=7$)
 387 and $17.0 \pm 1.3\text{‰}$ ($n=12$) (Fig. 7). As sulfur is a crucial microelement for plant metabolism,
 388 and as the main source for the plants is taken from the soil through the roots, with a limited
 389 isotopic fractionation between soil S and seed S (1‰; Tcherkez & Tea, 2013), hence the $\delta^{34}\text{S}$
 390 of Aghmat charred seeds may enhance the hypothesis of two distinct cultivation areas with
 391 distinct soil $\delta^{34}\text{S}$. To our knowledge, no direct studies providing the $\delta^{34}\text{S}$ of the soil in the very
 392 specific area of Aghmat is available. However, in the Amensif ore deposit located in the
 393 Haouz plain, at about 57 km SW of our study area, Jinari et al. (2023) identified two distinct
 394 groups of $\delta^{34}\text{S}$ values, one centered around 6 ‰ and the other between 11 and 15‰. If we
 395 take into account the concomitant $\delta^{15}\text{N}$ values carried out on charred seed remains (Fig. 6),
 396 we can suggest for this specific phase two to four different wheat and barley cultivated lands,
 397 characterized by different manure managements.

398 Regarding cereal cultivation, for each suggested lands, the small difference between
 399 values of $\delta^{15}\text{N}$ of barley and wheat suggests that both crops were grown under the same

400 manuring conditions (Fraser et al., 2011). Both barley and wheat $\delta^{15}\text{N}$ values reflect mixed
401 agricultural practices, likely with lands cultivated without manuring ($<3\text{‰}$), and lands
402 managed with low (4 to 6 ‰) to high ($>7\text{‰}$) manuring intensity (Bogaard et al., 2013; Styring
403 et al., 2016). It is difficult to disentangle the multiple causes of the $\delta^{15}\text{N}$ variations of both
404 cereal crops, and hence to explain precisely the farming conditions. The higher $\delta^{15}\text{N}$ may be
405 explained by stall manure input (with and offset of about 4 ‰ compared to unmanured crops;
406 Steele and Daniel, 1978), but also by soil types and environmental factors affecting soil
407 nitrogen isotopic composition, such as aridity and nitrogen loss (Fiorentino et al., 2014).
408 Using our $\delta^{15}\text{N}$ barley values and the annual precipitation reconstructed following Hartman &
409 Danin, (2010) and Styring et al., (2016) methods, our data plot in the no/low to medium
410 manuring level bands and in the low precipitation level (50 to 300 mm). These reconstructed
411 low precipitations are in agreement with the anomalies of precipitation described by Till &
412 Guiot (1990), showing several drought years and generally dryer conditions for the eleventh-
413 twelfth centuries, when the North Atlantic oscillation (NAO) is positive on the Mediterranean
414 Basin (before 1350 AD), as suggested by Esper et al. (2007), Trouet et al. (2009), and
415 Wassenburg et al., (2013), enhancing the hypothesis of the aridity impact on the $\delta^{15}\text{N}$ values.
416 These dryer conditions are also suggested by hulled barley $\Delta^{13}\text{C}$ (Fig. 8). Five barley samples
417 were under hydric stress, against only one for naked wheat, suggesting that wheat is
418 moderately to well-watered, likely through irrigation (Fig. 8). Including the sulfur isotopes
419 (Fig. 9), we identified four different groups of crops, cultivated in at least three different soils.
420 Barley cereal filling water input is on average 109 ± 45 mm (Appendix 4, 5), close to the SE
421 Spain values described by Araus et al. (1997) for older chronologies. In fact, when we
422 compare the WUEi values with Mora-Gonzales (2017), we observe that most of the wheat and
423 barley are below the proposed theoretical level of hydric stress ($85 \mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$,
424 Appendix 4). Even taking into account the limits for each species and the differences that
425 could be expected, irrigation appears as a likely solution adopted in most lands, with few
426 exceptions. However, the observed $\delta^{15}\text{N}$ barley range might also suggest different winter and
427 spring crop varieties, associated to different agronomic practices of local farmers in diverse
428 environments of the Haouz plain, or reflect imported crops.

429

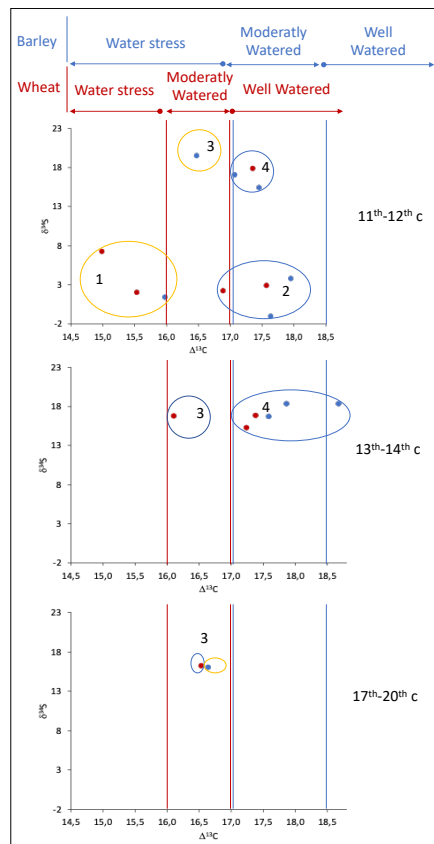


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431

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Figure 8: $\Delta^{13}\text{C}$ against $\delta^{15}\text{N}$ of both barley (left panel) and wheat (right panel)



433

434

435

436

Figure 9: $\Delta^{13}\text{C}$ against $\delta^{34}\text{S}$ of both hulled barley (blue) and naked wheat (red), using Wallace *et al.*, 2013 thresholds.

437 ***Aghmat's last centuries (thirteenth-fourteenth centuries)***

438 After this golden age, the city persists for another two centuries before being impacted by the
 439 wider economic crisis affecting Morocco during the fourteenth century, resulting in
 440 abandonment by its elites. The two centuries leading up to this abandonment show subtle
 441 differences from the previous phase in terms of supply strategies, particularly for fuel. Firstly,
 442 we note changes in the relative importance of the various fruit taxa, with the disappearance of
 443 grapevine and fig tree in the anthracological spectrum, while we observe a significant increase

444 in the Maloideae, from 10% to 21%, and the olive tree, from 5.8% to 12%. At the same time,
445 the proportion of riparian species increases (from 15.8 to 25%), while the proportion of oak
446 forest species remains stable, although with a significant increase in the proportion of araar
447 trees. These variations in fuel composition could be explained by a change in resources
448 availability: a reduction in the fruitwood resource could have led to more intensive
449 exploitation of certain nearby areas, in particular the Ourika riverbanks. The increase in the
450 proportion of Maloideae is difficult to interpret, as these may correspond to cultivated fruit
451 species (e.g. *Malus*, *Pyrus*) as well as hedge or forest edge species (e.g. *Crataegus*, *Rosa*). In
452 terms of consumed species, there is continuity, both in the exploited diversity and in the type
453 of remains encountered, with the appearance of three new fruit trees: the almond (*Prunus*
454 *dulcis*), the date palm (*Phoenix dactylifera*) and the jujube (*Ziziphus* sp.). Although palm and
455 jujube trees were known in southern Morocco at this time, this is the first archaeobotanical
456 record of almond tree in the country (Ruas 2018). The local nature of the encountered fruit
457 species is debatable; charcoal analysis confirms the presence of pomegranate, olive and
458 possibly apricot/almond/peach trees (Rosaceae prunoideae with large rays) in the local
459 landscape.

460

461 The frequency of cereals in the samples indicates their central role in the diet of urban
462 populations during this period. The question remains as to whether they came from local or
463 imported sources. The narrow range of variations of the $\delta^{34}\text{S}$ of hulled barley (16.7 to 18.3 ‰)
464 and naked wheat (from 15.3 to 16.9 ‰) contrasts with the previous period, highlighting that
465 crops were cultivated in the same region/land. These seeds were grown under no/low to
466 medium manure inputs, as shown with $\delta^{15}\text{N}$ range values of both hulled barley (3.7 to 8.6 ‰)
467 and naked wheat (from 3.4 to 8.0 ‰). Generally, the conditions of crop cultivation seem
468 moderately-watered, as suggested by the $\Delta^{13}\text{C}$ (16.5 ‰ for wheat and 17.7 ‰ for barley) and
469 WUEi with values below 85 $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$ (Appendix 4, 5). If we focus on barley
470 WUEi, it is likely that climate conditions were slightly wetter compared to the previous period
471 (71.8 and 78.2 $\mu\text{mol CO}_2 \text{ mol}^{-1} \text{ H}_2\text{O}$, respectively) in agreement with the negative North
472 Atlantic Oscillation (NAO) phase with cooler and wetter conditions downwards from 1300
473 AD onwards (Esper et al., 2007; Trouet et al., 2009).

474

475 ***Towards the ruralization of Aghmat (fifteenth-sixteenth centuries)***

476 Archaeological excavations in this phase indicate a clear ruralization of the town, reflected in
477 both material culture and architectural changes. For example, we identified in the palatial

478 complex of the site the construction of mud walls aimed at redefining the internal spaces. The
479 natural resources exploited during this period also bear witness to a radical change. As a
480 result, riparian vegetation has almost completely disappeared, with rare monocotyledons
481 being the last possible evidence of its existence. Regarding the exploitation of the oak forest,
482 *Tetraclinis* has disappeared, *Fraxinus* is still present, and *Quercus* has increased significantly,
483 rising from 2.1% in the 14th c. to 23% in the sixteenth century. But the most notable change
484 concerns fruit trees: only pomegranate and olive remain in the spectrum, the latter alone
485 accounting for 62% of the charcoal fragments studied for this phase. This sudden boom of
486 olive proportions in the anthracological spectrum is remarkable, and the question arises as to
487 whether these results are a sign of the emergence of a specialized production area, the
488 economic scope of which remains to be defined (local, regional production?). The sudden
489 disappearance or decline of the riparian vegetation, *Tetraclinis* and *Fraxinus* seems more
490 difficult to explain: does it depend on climatic factors, leading to the instability of the Ourika
491 riverbanks and to conditions unfavorable for some forest species, such as *Tetraclinis* and
492 *Fraxinus*? Or on the development of certain crops which have taken the place of said species,
493 for example by dedicating the Ourika riverbanks to olive cultivation? Or to the rise of other
494 practices that our approach cannot highlight, such as pastoralism, some species, such as
495 *Fraxinus*, being particularly affected by grazing? The data needs to be amplified before a
496 more solid hypothesis can be proposed.

497 Changes are also observed in agrohorticultural production, although not in terms of the
498 consumed/exploited diversity, since the spectrum remains broadly the same, although two
499 new taxa appeared: peach (*Prunus persica*) and common millet (*Panicum miliaceum*). It is
500 interesting to note that, until now, only sites in the north of Morocco have yielded millet, the
501 main medieval site in the south, Îgîlîz, having yielded another Panicoideae, sorghum (Ruas
502 2018). Another striking difference with the previous phase is the discovery in one of the
503 houses of cereal threshing by-products, composed of cereals (oat, probably *Avena fatua*, and
504 barley), mixed with rachis (barley, naked wheat) and numerous seeds of wild plants, mainly
505 grasses (see Appendix 1). This sample is the first indisputable evidence of local cereal
506 production and processing within the ruralized city. Most of the weeds encountered in this
507 sample are winter therophytes growing on dry, clayey soils (i.e. *Anthemis cotula*, *Avena fatua*,
508 *Lolium temulentum*, *Medicago polymorpha*, *Sherardia arvensis*), which is consistent with the
509 immediate surroundings of the site.

510

511 ***Aghmat becomes a village (seventeenth-twentieth centuries)***

512 This phase is the least understood for the site, due to the scarcity of excavated contexts. From
513 an archaeobotanical point of view, only one sample was studied, which yielded both charcoal
514 and seeds; for this reason, the proposed results are exploratory and need to be strengthened. It
515 should be noted, however, that this is the only modern/contemporary archaeobotanical sample
516 studied in Morocco to date.

517 In terms of tree vegetation, the trends observed during the previous phase seem to be
518 strengthening, with the proportion of olive trees increasing still (91% of the identified
519 charcoal fragments), and forest species decreasing further (less than 1% oak). Some species
520 appear to make a tentative comeback, particularly the riverbank species, perhaps as a result of
521 different management of this area. For the time being, the Aghmat Ourika riverbanks have
522 been preserved, and tree vegetation is fully developing. As far as agriculture is concerned, the
523 diversity is similar to that identified in the previous phases (barley, naked wheat, fig, date,
524 grapevine, and flax), but the sample does not allow us to ascertain the local nature of these
525 crops, apart from the fig and pomegranate trees, identified by charcoal fragments. Regarding
526 agricultural practices derived from stable isotopes, the small number of samples available for
527 this period does not permit strong conclusions. The very similar $\delta^{34}\text{S}$ values for naked wheat
528 (16.2 ‰) and barley (16.1 ‰) suggest these two cereals were probably grown in the same
529 region or on land in close proximity, and likely cultivated with higher levels of manure inputs
530 compared to the previous periods, as shown by the $\delta^{15}\text{N}$, especially for wheat (8.0 ± 1.4 ‰) in
531 comparison with barley (6.1 ± 0.5 ‰). $\Delta^{13}\text{C}$, WUEi and the water input for naked wheat and
532 hulled barley (Fig. 8, 9, Appendix 1, 4, 5, 6) suggest these crops were generally moderately
533 watered. The mean nitrogen and carbon contents of the wheat and barley crops are the highest
534 compared to the previous periods in agreement with the increase of manure inputs all along
535 the three studied periods.

536

537 **Conclusion**

538 Our interdisciplinary pilot study makes it possible to establish for the first time the
539 agricultural and forestry dynamics over the last millennium in this region that seem related to
540 changes that are essentially socio-economic in nature, but may also be environmental.

541 Although the exploited species appear to have remained relatively stable, their relative
542 importance and frequency suggest a change in practices, which can no doubt be linked to
543 changes in economic priorities when the settlement's status changed at the end of the Middle
544 Ages. Environmental conditions would have favored regional or even local farming that did

545 not necessarily require large-scale irrigation, at least not for cereal growing, the question
546 remaining open for fruit growing.

547 These various results represent the completion of a first stage of work, which is now
548 being continued in the form of a doctoral thesis (Badri ongoing). One of the medium-term
549 objectives is to strengthen the archaeobotanical approach by analyzing over a hundred new
550 samples from different sectors and phases of the site. Isotopic analysis will be further
551 developed by creating a current local reference base, including both cereals and fruit trees
552 (grapevine, olive), as they are key elements of the local agricultural system over the last
553 millennium. In addition, two cutting-edge approaches will be carried out on the remains of
554 fruit trees. Firstly, a geometric morphometry approach will be applied to the archaeological
555 grape seeds and olive stones (Terral et al., 2004, 2010), with the aim of shedding light on the
556 varieties used and how they may have changed over time. Lastly, a quantitative eco-
557 anatomical approach will be applied to olive trees charcoals (Terral 2000), to highlight any
558 irrigation of this species over time.

559

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562 the workers and colleagues who, for the past 15 years, took a part in the excavation and study of the site,
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568

569 **DECLARATIONS**

570 **Ethical Approval**

571 Not applicable

572

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575 Orient & Méditerranée, and the PEPS INEE-NOURANAT 2020 "AGHMAT: Agrosystèmes
576 Historiques du Maroc: Adaptations, Transformations - L'exemple de la région du Haouz".

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578

579 **REFERENCES**

580 Achhal, A. (1979). Le chêne vert dans le Haut Atlas central : Etude phytoécologique et
581 problèmes posés par les aménagements de la chênaie. Dissertation, Univ. Droit, Econom. Sc.
582 Aix, Marseille III.

583

584 Al-Bakrî (1911). *Kitâb al-masâlik wa- 'l-mamâlik*, 2nd edition, W. Mac Guckin de Slane (ed.),
585 A. Jourdan, Algiers.

586

587 Al-Idrîsî (1866). *Description de l'Afrique et de l'Espagne*, R. Dozy and M. J. De Goeje (ed.
588 and transl.), Brill, Leiden.

589

590 Ait El Mekki, O., & Laftouhi, N-E. (2016). Combination of a geographical information system
591 and remote sensing data to map groundwater recharge potential in arid to semi-arid areas: the
592 Haouz Plain, Morocco. *Earth Sci Inform.* <https://doi.org/10.1007/s12145-016-0268-0>

593

594 Allevato, E., Pecci, A., Papi, E., & Di Pasquale, G. (2013). Evidence from charcoal analysis for
595 the extensive exploitation of cork-oak (*Quercus suber*) forest in the roman imperial period: the
596 vicus of Thamusida (nw morocco). In F. Damblon (ed.), *Proceedings of The Fourth*
597 *International Meeting Of Anthracology*, Brussels, 8-13 September 2008 Royal Belgian Institute
598 of Natural Sciences, BAR International Series n° 2486, Oxford, 11-17.

599

600 Allevato, E., Buonincontri, M. P., Pecci, A., D'Auria, A., Papi, E., Saracino, A., & Di Pasquale,
601 G. (2016). Wood exploitation and food supply at the border of the Roman Empire: the case of
602 the vicus of Thamusida - Sidi Ali ben Ahmed (Morocco). *Environmental Archaeology*, n° 22-
603 2, 200-217. <https://doi.org/10.1080/14614103.2015.1126685>

604

605 Araus, J.L., Febrero, A., Buxo, R., Camalich, M.D., Martin, D., Molina, F., Rodriguez-Ariza,
606 M.O., & Romagosa, I. (1997). Changes in carbon isotope discrimination in cereal cereals from
607 different regions of the western Mediterranean Basin during the past seven millennia.
608 Palaeoenvironmental evidence of a differential change in aridity during the late Holocene.
609 *Global Change Biology*, 3, 107-118. <https://doi.org/10.1046/j.1365-2486.1997.00056.x>

610

- 611 Barbéro, M., Quézel, P., & Rivas-Martínez, S, (1981). Contribution à l'étude des groupements
612 forestiers et préforestiers du Maroc. *Phytocoenologia*, 9, 3, 311-412.
613 <https://doi.org/10.1127/phyto/9/1981/311>
614
- 615 Benabid, A. (1982). Etude phytoécologique, biogéographique et dynamique des associations et
616 séries sylvatiques du Rif occidental (Maroc). Dissertation. Univ. Droit, Econom., Sc., Aix-
617 Marseille III.
618
- 619 Benabid, A. (1985). Les écosystèmes forestiers, préforestiers et presteppiques du Maroc :
620 diversité, répartition biogéographique et problèmes posés par leur aménagement. *Forêt*
621 *Méditerranéenne* VII (1), 53-64.
622
- 623 Bogaard, A., Fraser, R., Heaton, T.H.E., Wallace, M., Vaiglova, P., Charles, M., Jones, G.,
624 Evershed, R.P., Styring, A.K., Andersen, N.H., Arbogast, R.-M., Bartosiewicz, L., Gardeisen,
625 A., Kanstrup, M., Maier, U., Marinova, E., Ninov, L., Schäfer, M., & Stephan, E. (2013). Crop
626 manuring and intensive land management by Europe's first farmers. *Proc. Natl. Acad. Sci.* 110,
627 12589–12594. <https://doi.org/10.1073/pnas.1305918110>
628
- 629 Bourin-Derruau, M. (1987). *Villages médiévaux en Bas-Languedoc - Genèse d'une sociabilité*
630 *(Xe-XIVe siècle)*. L'Harmattan, Paris.
631
- 632 Cappers, R.T.J., Bekker, R.M., & Jans, J.E.A. (2006). *Digital Seed Atlas of the Netherlands*.
633 Barkhuis Publishing and Groningen University Library, Groningen.
634
- 635 Carrato, C., Ichkhakh, A., Kbir Alaoui, M., Rocca, E., Ruas, M.-P. et al. (2020). Recent
636 Discovery of an Urban Winery in Rirha (Sidi Slimane, Morocco), 2nd–3rd Century CE. In J.-
637 P. Brun, N. Garnier, G. Olcese. Making Wine in Western-Mediterranean / Production and the
638 Trade of Amphorae: Some New Data from Italy, Panel 3.5, Archaeology and Economy in the
639 Ancient World 9, *Archaeology and Economy in the Ancient World (9)*, pp.167-175.
640
- 641 Demians d'Archimbaud, G. (1982). *Les fouilles de Rougiers, Contribution à l'archéologie de*
642 *l'habitat rural médiéval en pays méditerranéen*. Editions du C.N.R.S., Paris.
643

- 644 Du, B., Zheng, J., Ji, H., Zhu, Y., Yuan, J., Wen, J., Kang, H., & Liu, C. (2021). Stable carbon
645 isotope used to estimate water use efficiency can effectively indicate seasonal variation in leaf
646 stoichiometry. *Ecological Indicators* 121, 107250.
647 <https://doi.org/10.1016/j.ecolind.2020.107250>
648
- 649 Durand, A. (1998 réed 2003). *Les paysages médiévaux du Languedoc (Xe-XIIIe siècles)*, Presses
650 Universitaires du Mirail, Toulouse.
651
- 652 Farquhar, G.D., O'Leary, M.H., & Berry, J.A. (1982). On the Relationship Between Carbon
653 Isotope Discrimination and the Intercellular Carbon Dioxide Concentration in Leaves. *Funct.*
654 *Plant Biol.* 9, 121–137. <https://doi.org/10.1071/PP9820121>
655
- 656 Farquhar, G.D., Ehleringer, J.R., & Hubick, K.T. (1989). Carbon isotope discrimination and
657 photosynthesis. *Annual Review of Plant Biology* 40(1), 503–537.
658 <https://doi.org/10.1146/annurev.pp.40.060189.002443>
659
- 660 Fennane, M. (1988). Phytosociologie des tétraclinaies marocaines. *Bull. Inst. Sei.*, Rabat 12,
661 99-148.
662
- 663 Ferrio, J.P., Bort, J., Voltas, J., & Araus, J.L. (2004). Past climate and agricultural water
664 management in the Mediterranean inferred from carbon isotope discrimination in
665 archaeological plant remains. In A. Hamdy, M. Tüzün, N. Lamaddalena, M. Todorovic, C.
666 Bogliotti (Es). *Participatory water saving management and water cultural heritage*. CIHEAM
667 Options Méditerranéennes : Série B. Etudes et Recherches; n. 48, Bari, pp. 289-296.
668
- 669 Ferrio, J.P., Araus, J.L., Buxó, R., Voltas, J., & Bort, J. (2005). Water management practices
670 and climate in ancient agriculture: inferences from the stable isotope composition of
671 archaeobotanical remains. *Veg. Hist. Archaeobotany* 14, 510–517.
672 <https://doi.org/10.1007/00334-005-0062-2>
673
- 674 Fiorentino, G., Ferrio, J.P., Bogaard, A., Araus, J.L., & Riehl, S. (2014). Stable isotopes in
675 archaeobotanical research. *Veget Hist Archaeobot.* <https://doi.org/10.1007/s00334-014-0492-9>
676

- 677 Fourel, F., Martineau, F., Seris, M., & Lécuyer, C. (2014). Simultaneous N, C, S stable isotope
678 analyses using a new purge and trap elemental analyzer and an isotope ratio mass spectrometer.
679 *Rapid Commun. Mass Spectrom.* 28, 2587–2594. <https://doi.org/10.1002/rcm.7048>
680
- 681 Francey, R.J., Allison, C.E., Etheridge, D.M., Trudinger, C.M., Enting, I.G., Leuenberger, M.,
682 Langenfelds, R L., Michel, E., & Steele, L P. (1999). A 1000-year high precision record of $\delta^{13}\text{C}$
683 in atmospheric CO_2 . *Tellus B, Chemical and Physical Meteorology*, 51, 170–193.
684
- 685 Fraser, R., Bogaard, A., Heaton, T., Charles, M., Jones, G., Christensen, B., Halstead, P.,
686 Merbach, I., Poulton, P., Sparkes, D., & Styring, A. (2011). Manuring and Stable Nitrogen
687 Isotope Ratios in Cereals and Pulses: Towards a New Archaeobotanical Approach to the
688 Inference of Land Use and Dietary Practices. *Journal of Archaeological Science*, 38, 2790–804.
689 <https://doi.org/10.1016/j.jas.2011.06.024>
690
- 691 Fuller, D. (2002). Environmental Archaeology at Volubilis 2002: archaeobotany,
692 archaeozoology and phosphate analysis. In E. Fentress, H. Limane, G. Palumbo, (dir.), *The*
693 *UCL/INSAP Volubilis Project Excavation, Management and Conservation, April and October*
694 *2002*, Excavation report, pp. 9-11.
695
- 696 Fuller, D. (2004). Archaeobotanical work, 2004. In E. Fentress, H. Limane, G. Palumbo (dir.),
697 *Excavation and Conservation at Volubilis, 2004*, pp. 8-9.
698 https://sitedevolubilis.org/wp-content/uploads/2021/06/2004_Report.pdf
699
- 700 Fuller, D. Q., Stevens, C. J. (2009). Agriculture and the development of complex societies: an
701 archaeobotanical agenda. In A. Fairbairn, E. Weiss (eds), *From Foragers to Farmers: Papers*
702 *in Honour of Gordon C. Hillman*, Oxford: Oxbow Books, pp. 37-57.
703
- 704 Fuller, D. Q., Pelling, R. (2018). Plant Economy: Archaeobotanical Studies. In E. Fentress, H.
705 Limane (Eds), *Volubilis après Rome: Les fouilles UCL/INSAP, 2000-2005 (Arts and*
706 *Archaeology of the Islamic World)*, Leiden: Brill, pp. 349-368.
707
- 708 Grau Almero, E., Pérez, Jordà, G., Iborra Eres, M. P., Rodrigo Garcia, M. J., Rodriguez
709 Santana, C. G., & Carrasco Porras, M. S. (2001). Gestión de recursos y economía. In C.

- 710 Aranegui Gascó, M. Habibi (Eds.), *Lixus, colonia fenicia y ciudad púnico-mauritana.*
711 *Anotaciones sobre su ocupación medieval*, Saguntum, extra 4, pp. 191-230.
712
- 713 Grau Almero, E., Pérez Jordà, G., & Iborra Eres, M. P. (2010). La gestión de los recursos
714 naturales. In C. Aranegui Gascó, H. Hassini (Eds.), *Lixus-3. Area suroeste del sector*
715 *monumental [Camaras Montalban] 2005-2009*, Saguntum Extra 8, pp. 61-68.
716
- 717 Hartman, G., Danin A. (2010). Isotopic values of plants in relation to water availability in the
718 Eastern Mediterranean region. *Oecologia*, 162, 837–852. [https://doi.org/10.1007/s00442-009-](https://doi.org/10.1007/s00442-009-1514-7)
719 [1514-7](https://doi.org/10.1007/s00442-009-1514-7)
720
- 721 Héritier-Salama, V. (2019). Canaux anciens et puits récents : usages de l'eau d'irrigation,
722 identité et territoire dans le Haouz (Maroc). *Développement durable et territoires : économie,*
723 *géographie, politique, droit, sociologie*, 10–3.
724
- 725 Héritier-Salama, V., Capel, C., Fili, A., & Messier, R. (2016). De la ville aux champs. La
726 transformation d'Aghmat (Maroc) entre les X^{IV}e et X^{VI}e siècles. In C. Müller, M. Heintz
727 (Eds), *Transitions historiques*. Editions de Boccard, Paris, pp. 195-207.
728
- 729 Jacomet, S. (2006). *Identification of cereal remains from archaeological sites*. 2nd edition,
730 Archaeobotany laboratory IPAS, Basel University.
731
- 732 Jacquot, C. (1955). *Atlas d'anatomie des bois des Conifères*. 2 vol., Centre technique du bois,
733 Paris.
734
- 735 Jacquot, C., Trenard, Y., & Dirol, D. (1973). *Atlas d'anatomie des bois des Angiospermes*
736 *(Essences feuillues)*. Centre technique du bois, Paris.
737
- 738 Jinari, A., Rddad, L., Mouguina, E-M., & Ouadjou, A. (2023). Origin of the Amensif Zn-Cu
739 (Pb-Ag-Au) distal skarn deposit (Western High Atlas, Morocco): Constraints from C-O-S
740 isotopes. *Journal of African Earth Sciences* 199 (2023) 104850.
741 <https://doi.org/10.1016/j.jafrearsci.2023.104850>
742

743 Köppen, W. (1936). Das geographische System der Klimate, *Gebrüder Borntraeger*, Berlin,
744 Germany, pp. 1-44.

745

746 Leuenberger, M., Siegenthaler, U., & Langway, C. (1992). Carbon isotope composition of
747 atmospheric CO₂ during the last ice age from an Antarctic ice core. *Nature* 357, 488–490.
748 [https://doi.org/ 10.1038/357488a0](https://doi.org/10.1038/357488a0)

749

750 Maxwell, T.M., Silva, L.C.R., & Horwath, W.R. (2018). Integrating effects of species
751 composition and soil properties to predict shifts in montane forest carbon-water relations. *Proc.*
752 *Natl. Acad. Sci. U. S. A.* 115, E4219–E4226. <https://doi.org/10.1073/pnas.1718864115>

753

754 Mora-Gonzales, A., (2017). Irrigacion y secano en el Mediterraneo occidental (III-I milenio
755 a.n.e): un estudio isotopico. Dissertation, Facultad de Filosofia y letras, Universida de Granada.

756

757 Nitsch, E.K., Charles, M., & Bogaard, A. (2015). Calculating a statistically robust $\delta^{13}\text{C}$ and
758 $\delta^{15}\text{N}$ offset for charred cereal and pulse seeds. *STAR Sci. Technol. Archaeol. Res.* 1, 1–8.
759 <https://doi.org/10.1179/2054892315Y.0000000001>

760

761 Nourissier, A., Nocus, N., & Dufraisse, A., (2016). ACACIA: *Automatical Creation of*
762 *Anthracological Diagram. The User Guide.* Available on
763 <https://dendrac.mnhn.fr/spip.php?rubrique69>

764

765 Ouerfelli, M. (2010). L'exploitation et la gestion des forêts dans le Maghreb médiéval. *Les*
766 *ressources naturelles au Maghreb durant l'Antiquité et le Moyen Age : exploitation, gestion et*
767 *usages. Ve colloque international de l'Unité de Recherche Peuplement et Mise en valeur en*
768 *Tunisie à travers l'Histoire*, 25-2, Tunis, Tunisie, 41-77.

769

770 Ouerfelli, M., Voguet, E. (2009). *Le monde rural dans l'Occident musulman médiéval*,
771 REMMM 126 2009-2, Aix-en-Provence, PUP.

772

773 Ouhammou, A., Aubin, P. (1991). II - Aperçu sur l'étagement de la végétation du bassin de
774 l'Ourika (Haut-Atlas de Marrakech, Maroc). *Bulletin mensuel de la Société linnéenne de Lyon*,
775 60e année, 10, 401-405.

776

- 777 Peña-Chocarro, L., Pérez- Jordà, G., Alonso, N., Antolín, F., Teira-Brión, A., Pedro Tereso, J.,
778 Montes Moya, E., López Reyes, D. (2019). Roman and medieval crops in the Iberian Peninsula:
779 A first overview of seeds and fruits from archaeological sites. *Quaternary International*,
780 Volume 499, Part A, 2019, 49-66. ISSN 1040-6182.
781 <https://doi.org/10.1016/j.quaint.2017.09.037>
782
- 783 Pérez Jordà, G. (2005). Estudio paleocarpológico. In C. Aranegui Gascó, M. Habibi (Eds.),
784 *Lixus-2. Ladera sur. Excavaciones arqueológicas marroco-españolas en la colonia fenicia.*
785 *Campañas 2000-2003*, Saguntum, extra 6, pp. 221-227.
786
- 787 Pollock, S. (1986). Progress report on plant remains from Badis, al-Basra and Qsar es Seghir.
788 *Bull. d'archéol. Marocaine*, n°15, 355–360.
789
- 790 Puig, C. (2003). *Les campagnes roussillonaises au Moyen Age : dynamiques agricoles et*
791 *paysagères entre le XIIème et la première moitié du XIVème siècle*. Dissertation, Université de
792 Toulouse-Le Mirail.
793
- 794 Quézel, P., Médail, F. (2003). *Ecologie et biogéographie des forêts du bassin méditerranéen.*
795 Elsevier, Paris.
796
- 797 Rameau, J.-C., Mansion, D., & Dume, G. (2008). *Flore forestière française, guide écologique*
798 *illustrée. Tome 3: région méditerranéenne*. Institut pour le Développement Forestier, CNPPF,
799 Forêt Privée Française, IDF.
800
- 801 Reimer, P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P.G., Bronk Ramsey, C., Butzin,
802 M., Cheng, H., Edwards, L.R., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I.,
803 Heaton, T.J., Hogg, A.G., Hughen, K.A., Kromer, B., Manning, S.W., Muscheler, R., Palmer,
804 J.G., Pearson, C., van der Plicht, J., Reimer, R.W., Richards, D.A., Scot, E.M., Southon, J.R.,
805 Turney, C.S.M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S.M., Fogtman-
806 Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto,
807 M., Sookdeo, A., & Talamo, S. (2020). The IntCal20 northern hemisphere radiocarbon age
808 calibration curve (0–55 cal kBP). *Radiocarbon*, 62, 725–757.
809 <https://doi.org/10.1017/RDC.2020.41>
810

- 811 Ros, J. (2020). *2000 ans d'agriculture en Roussillon, Productions végétales et terroirs*
812 *protohistoriques, antiques et médiévaux*. Éditions Mergoïl, collection Archéologie des Plantes
813 et des Animaux, 07.
- 814
- 815 Ros, J., Puig, C., & Ruas, M-P. (2014). Les denrées végétales dans le nord de la Catalogne
816 d'après les sources historiques et archéobotaniques (Xe-XVe siècles) : productions et échanges.
817 *Archéologie du Midi Médiéval* 32, 123-138.
- 818
- 819 Ros, J., Gilotte, S., Sénac, P., Gasc, S., & Gibert, J. (2019). Alimentación vegetal y agricultura
820 en los márgenes de al-Andalus: nuevos datos arqueobotánicos. In M. M. Delgado Pérez, L.-G.
821 Pérez-Aguilar (Eds), *Economía y Trabajo. Las Bases Materiales de la Vida en al-Andalus*,
822 Editions Alfar Universidad, Séville, pp. 43-80.
- 823
- 824 Ros, J., Badri, F.-E., Héritier-Salama, V., Capel, C., Fili, A., & Messier, R. (2021). First
825 archaeobotanical contribution to the history of food production and agriculture at Aghmat
826 (Morocco) between the 11th and the 17th c. *Journal of Archaeological Science: reports*,
827 Volume 38, August 2021, 102943. <https://doi.org/10.1016/j.jasrep.2021.102943>
- 828
- 829 Ruas, M.-P. (2005). Aspects of early medieval farming from sites in Mediterranean France.
830 *Vegetation History and Archaeobotany* 14 (4), 400-415. [https://doi.org/10.1007/s00334-005-](https://doi.org/10.1007/s00334-005-0069-8)
831 [0069-8](https://doi.org/10.1007/s00334-005-0069-8)
- 832
- 833 Ruas, M.-P. (2018). Fruits et légumes consommés au Maroc antique et médiéval : témoignages
834 archéobotaniques. In M. Oubalhi (Ed) *Manger au Maghreb-Partie IV : Par les mots, les fruits*
835 *et les légumes*, Presses Universitaires du Midi, Horizons Maghrébins, pp. 161-185.
- 836
- 837 Ruas, M.-P., Tengberg, M., Ettahiri, A. S., Fili, A., & van Staëvel, J.-P. (2011).
838 Archaeobotanical research at the medieval fortified site of Îgîlîz (Anti-Atlas, Morocco) with
839 particular reference to the exploitation of the argan tree. *Vegetation History Archaeobotany*
840 20(5), 419-433. <https://doi.org/10.1007/s00334-011-0306-2>
- 841
- 842 Ruas, M.-P., Ros, J., Terral, J.-F., Ivorra, S., Andrianarinosy, H., Ettahiri, A. S., Fili, A., & van
843 Staëvel, J.-P. (2016a). History and archaeology of the emblematic argan tree in the medieval

844 Anti-Atlas Mountains (Morocco), *Quaternary International*, Volume 'à', Part A, 6 June 2016,
845 114-136. <https://doi.org/10.1016/j.quaint.2015.09.030>

846

847 Ruas, M.-P., Figueiral, I., Heinz, C., & Ivorra, S. (2016b). Paléoenvironnement et
848 paléoéconomie d'après l'anthracologie et la carpologie. In L. Callegarin, M. Kbir Alaoui, A.
849 Ichkhakh (Dir), *Le site antique et médiéval de Rirha (Sidi Slimane, Maroc). Campagnes de*
850 *fouilles 2005-2009*, Casa Velázquez et INSAP, Rabat, pp. 42-109.

851

852 Saidi, M.E.M., Daoudi, L., Aresmouk, M.H., Fatima, F., & Boukrim, S. (2010). Les crues de
853 l'oued Ourika (Haut Atlas, Maroc) : événements extrêmes en contexte montagnard semi-aride.
854 *Comun. Geológicas* 97, 113–128.

855

856 Schweingruber, F.H. (1990). *Zwergstrauchhölzer = Anatomy of European woods: an atlas for*
857 *the identification of European trees*. Paul Haupt AG Verlag, Bern, 32-880.

858

859 Speciale, C., Bentaleb, I., Combourieu-Nebout, N., Di Sansebastiano, G.P., Ianni, F., Fourel,
860 F., & Giannitrapani, E. (2020). The case study of Case Bastione: First analyses of 3rd
861 millennium cal BC paleoenvironmental and subsistence systems in central Sicily. *J. Archaeol.*
862 *Sci. Rep.* 31, 102332. <https://doi.org/10.1016/j.jasrep.2020.102332>

863

864 Steele, K.W., Daniel, R.M. (1978). Fractionation of nitrogen isotopes by animals: A further
865 complication to the use of variations in the natural abundance of ^{15}N for tracer studies. *The*
866 *Journal of Agricultural Science* 90, 7–9.

867

868 Styring, A.K., Ater, M., Hmimsa, Y., Fraser, R., Miller, H., Neef, R., Pearson, J.A., & Bogaard,
869 A. (2016). Disentangling the effect of farming practice from aridity on crop stable isotope
870 values: A present-day model from Morocco and its application to early farming sites in the
871 eastern Mediterranean. *Anthr. Rev.* 3, 2–22. <https://doi.org/10.1177/205301961666307>

872

873 Tcherkez, G., Tea, I. (2013). $^{32}\text{S}/^{34}\text{S}$ isotope fractionation in plant sulphur metabolism. *New*
874 *Phytologist* 200, 44–53. <https://doi.org/10.1111/nph.12314>

875

876 Terral, J-F. (2000). Exploitation and management of the olive tree during prehistoric times in
877 Mediterranean France and Spain. *J. Archaeol. Sc.*, Volume 27, Issue 2, February 2000, 127-
878 133. <https://doi.org/10.1006/jasc.1999.0444>

879

880 Terral, J.-F., Alonso N., Buxo, R., Chatti, N., Fabre, L., Fiorentino, G., Marinval, P., Perez, G.,
881 Pradat, B., & Alibert, P. (2004). Historical Biogeography of olive domestication (*Olea europaea*
882 L.) as revealed by geometrical morphometry applied to Biological and Archaeological material.
883 *Journal of Biogeography* 31 : 63-77. <https://doi.org/10.1046/j.0305-0270.2003.01019.x>

884

885 Terral, J.F., Tabard, E., Bouby, L., Ivorra, S., Pastor, T., Figueiral, I., Picq, S., Chevance, J.B.,
886 Jung, C., Fabre, L., Tardy, C., Compan, M., Bacilieri, R., Lacombe, T., & This, P. (2010).
887 Evolution and history of grapevine (*Vitis vinifera*) under domestication: new morphometric
888 perspectives to understand seed domestication syndrome and reveal origins of ancient European
889 cultivars, *Ann. Bot.* 105, 443-455. <https://doi.org/10.1093/aob/mcp298>

890

891 Till, G., Guiot, J. (1990) Reconstruction of Precipitation in Morocco Since 1100 A.D. Based
892 on *Cedrus atlantica* Tree-Ring Widths. *Quaternary Research*, Volume 33, Issue 3, May 1990,
893 337-351. [https://doi.org/10.1016/0033-5894\(90\)90060-X](https://doi.org/10.1016/0033-5894(90)90060-X)

894

895 Vernet, J.L., Ogereau, P., Figueiral, I., Machado Yanès, C., & Uzquiano, P. (2001). *Guide*
896 *d'identification des charbons de bois préhistoriques et récents. Sud-Ouest de l'Europe :*
897 *France, Péninsule Ibérique et îles Canaries*, Paris, Editions du CNRS.

898

899 Wallace, M., Jones, G., Charles, M., Fraser, R., Halstead, P., Heaton, T.H.E., & Bogaard, A.
900 (2013). Stable carbon isotope analysis as a direct means of inferring crop water status and water
901 management practices. *World Archaeology* 45(3), 388-409.
902 <https://doi.org/10.1080/00438243.2013.821671>

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910 Appendix 1: Carpological raw data from Aghmat (SU= Stratigraphic Unit; fg.= fragment; XX= the taxa
911 is present).

Table with columns for Zone, IBC dating, SU, and various botanical taxa (e.g., TAXA, Fungi, Plant, etc.) across stratigraphic units. The table contains detailed counts for numerous species and sub-species, organized into a grid format with multiple columns for each taxon type.

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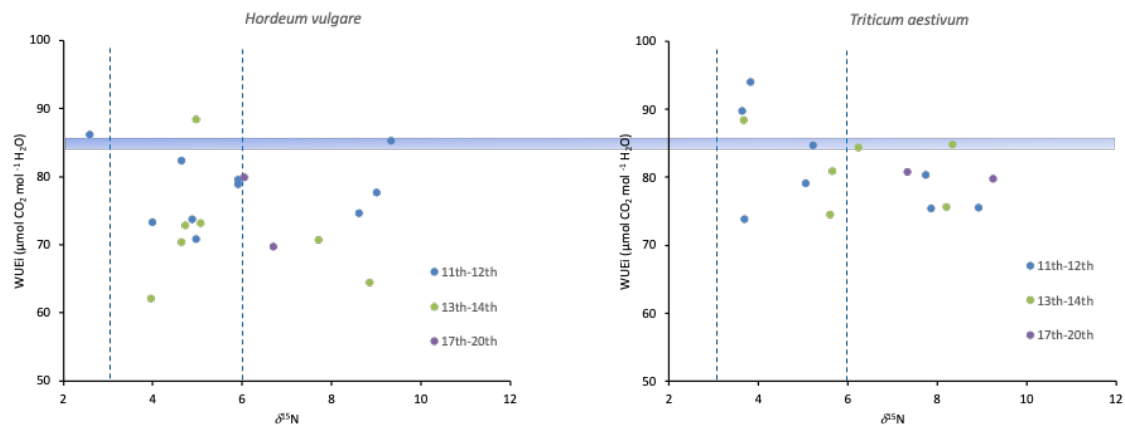
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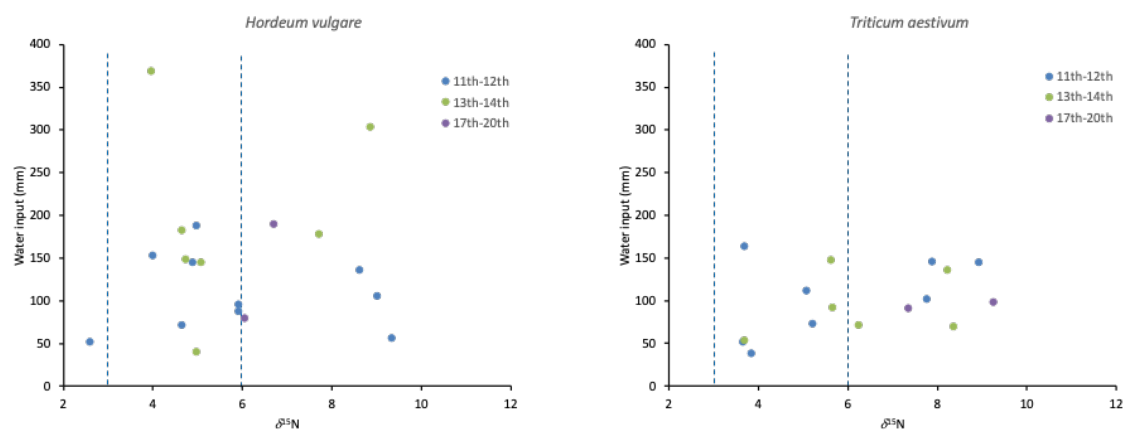
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Appendix 4: Water use efficiency against $\delta^{15}\text{N}$ of both barley (left panel) and wheat (right panel). The blue line represents the reference limit of hydric stress ($> 85 \mu\text{m}$)

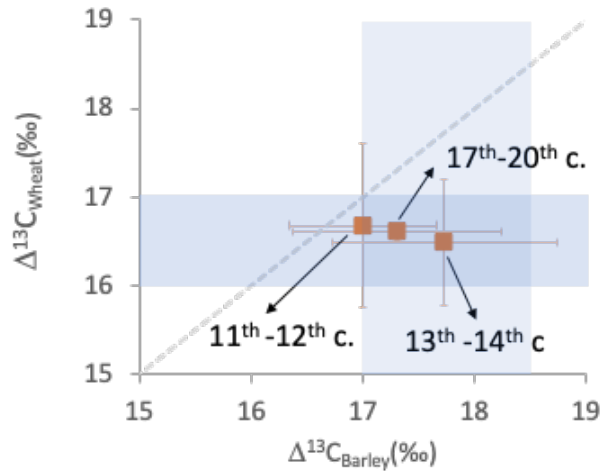


Appendix 5: Water input during cereal filling (mm) against $\delta^{15}\text{N}$ of both barley (left panel) and wheat (right panel)



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Appendix 6: Mean $\Delta^{13}\text{C}_{\text{Wheat}}$ against mean $\Delta^{13}\text{C}_{\text{Barley}}$ of the three studied periods at Aghmat. The blue shaded areas represent the water limits as described by Wallace et al. 2013.



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