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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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1 ISEM, UMR5554, Université Montpellier, CNRS, IRD, EPHE, Montpellier, France.

2 INSAP, Institut National des Sciences de l'Archéologie et du Patrimoine, Rabat, Maroc.

3 Faculté des lettres et des sciences humaines de l'Université Chouaib Doukkali, Université Al Jadida, El Jadida, Morocco,

4 UMR 5648 CIHAM, Université Lyon 2, EHESS, ENS Lyon, Avignon Université et Université Lyon 3, Lyon, France.

5 Chaire Emara, SAP+D, UM6P, Benguerir, Morocco.

6 UMR 8167-CNRS, Equipe Islam médiéval, Sorbonne Université, Paris I, EPHE, Collège de France, Paris, France.

7 School of History, Archaeology and Religion, Cardiff University, Cardiff, United Kingdom

8 LEHNA, UMR 5023, Université Lyon 1, ENTPE, CNRS, INRAE, Lyon, France.

9 Service du patrimoine culturel de l'Isère, Grenoble, France.

Corresponding Author: Jérôme Ros (jerome.ros@umontpellier.fr)

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.

57

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

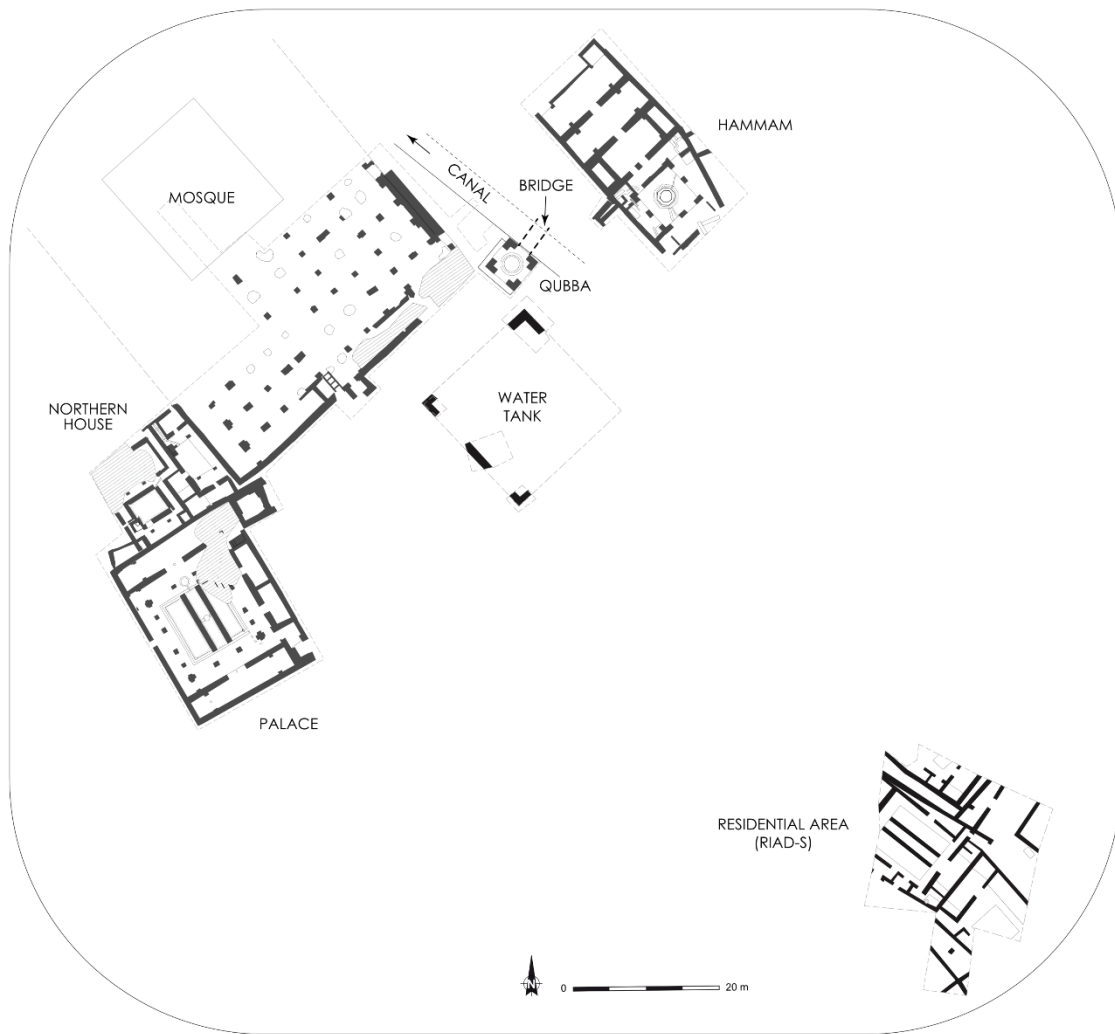
105

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

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Research Goals

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Materials and methods

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 (Jacquot, 1955; Jacquot 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).

161

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).

169

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

170

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).

221

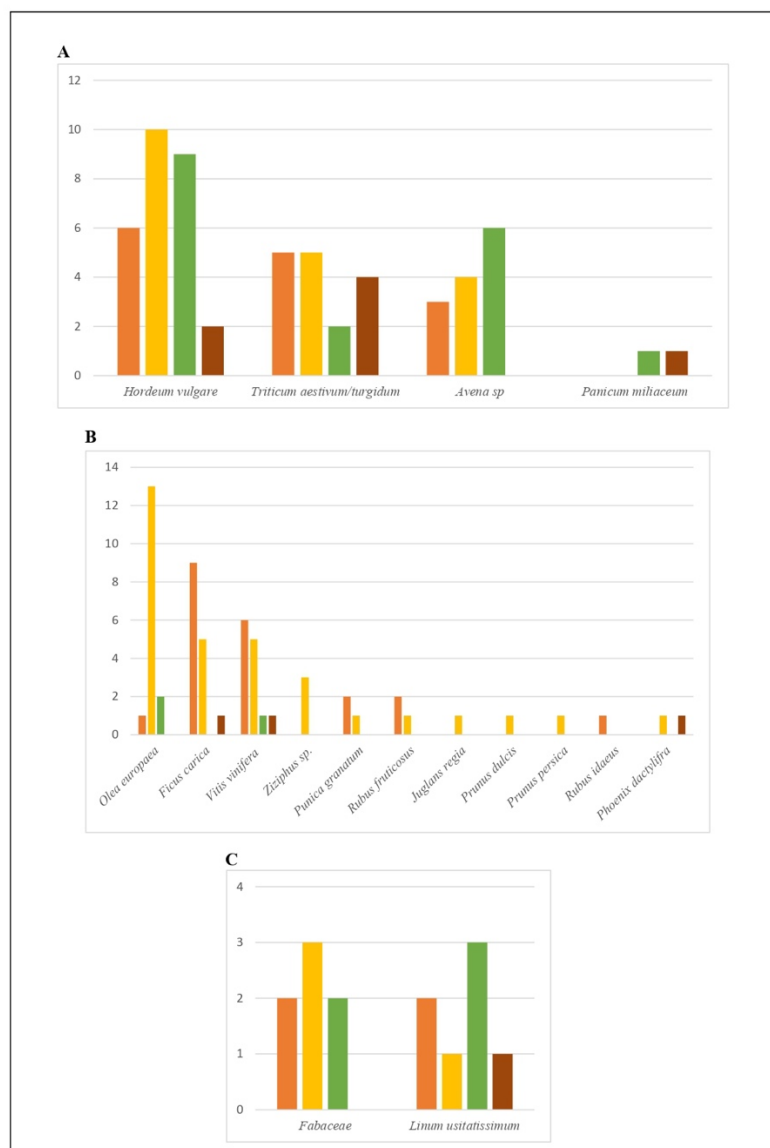
222 **Results**

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).

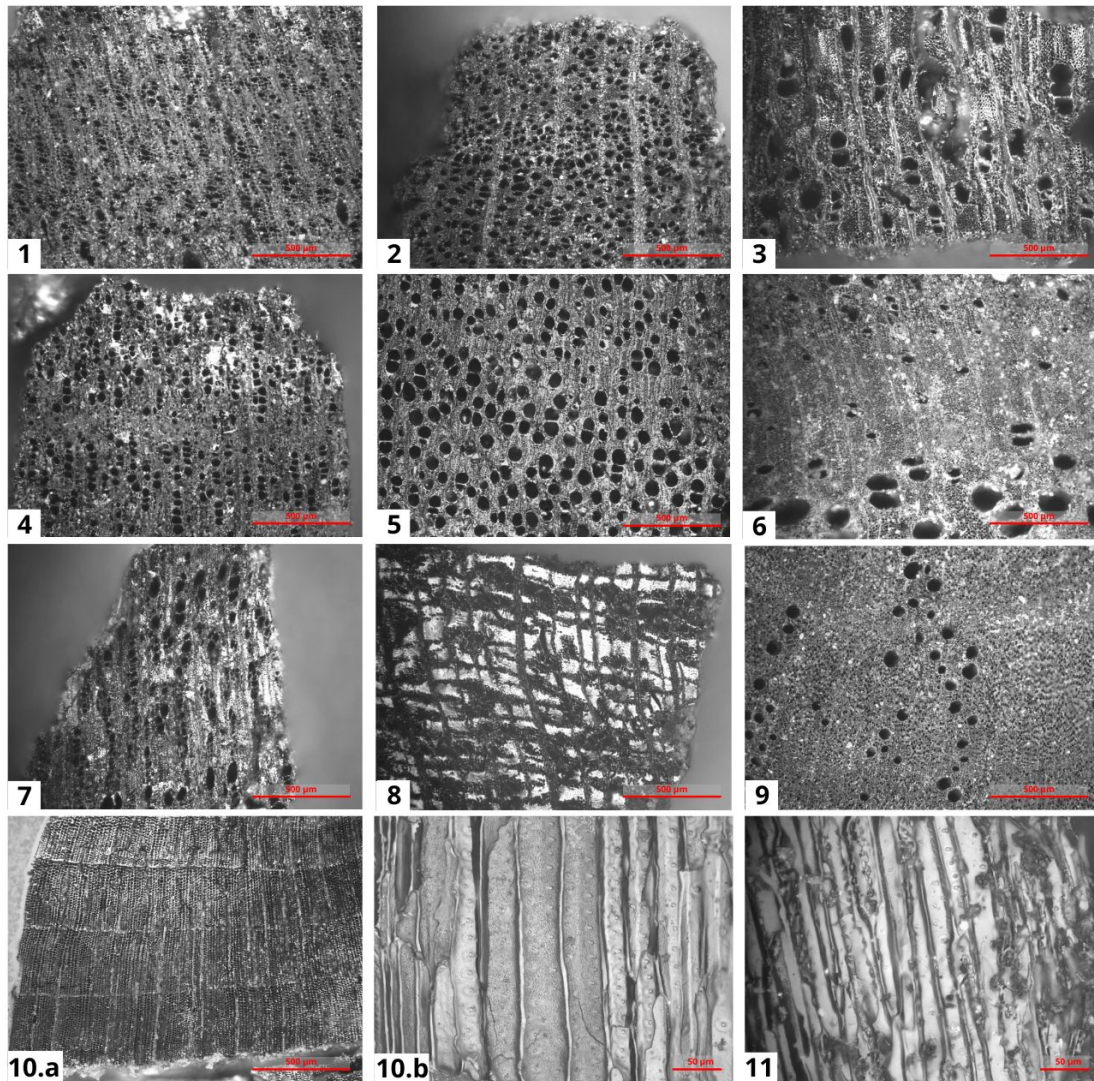


251 Fig. 3: Frequencies of carpological taxa (A: cereals; B: fruits; C: cultivated pulses and flax) for each phase (x
252 axis indicates the taxa; y axis indicates the number of contexts in which the taxa is recorded) (orange: 11th-12th
253 c.; yellow: 13th-14th; green: 15th-16th; brown: 17th-20th)
254

254

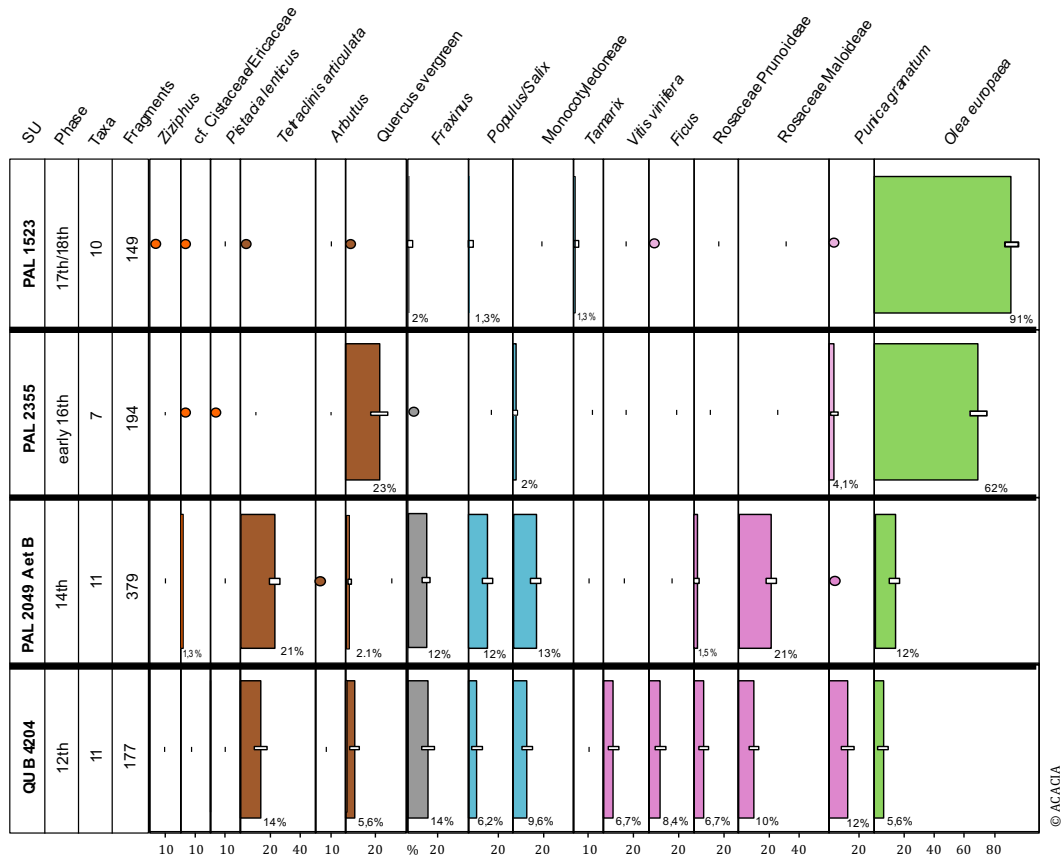
255 ***Charcoal remains***

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.



282

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.



289

290

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:

292

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.

294

295 *Charred seeds isotopic compositions*

296

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

300

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

301

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

302

records of barley and naked wheat, respectively.

303

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

304

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

305

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

306

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)

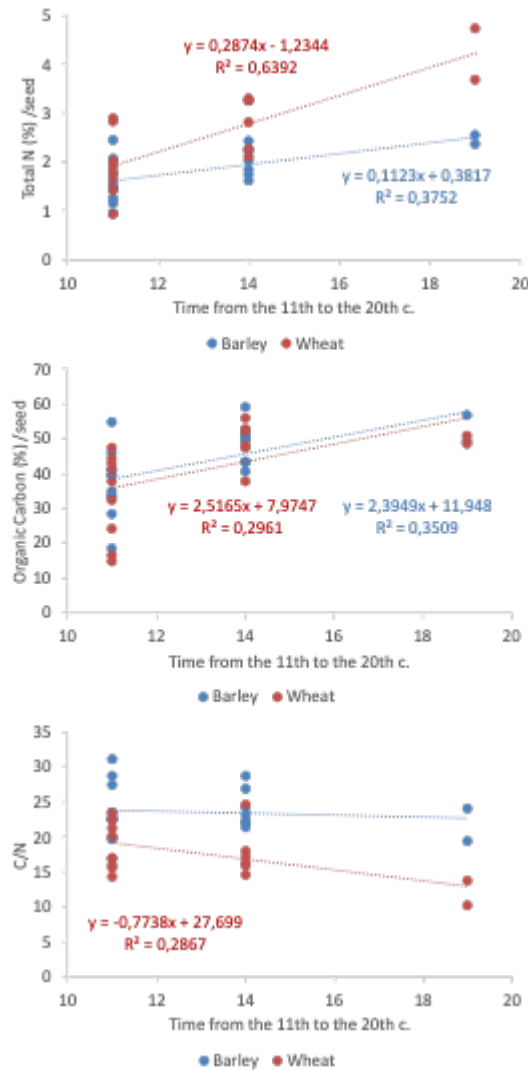
308 values ranging from 2.3 to 9.0 ‰ (mean value $5.6 \pm 1.9\%$) and $\delta^{13}\text{C}$ (n = 20) values ranging
309 from -24.9 to -21.6 ‰ (mean value $-23.3 \pm 0.8\%$), and $\delta^{34}\text{S}$ (n = 10) ranging from - 1.1 to
310 19.5 ‰ (mean value $12.5 \pm 7.9\%$). The mean values of C, N and 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).

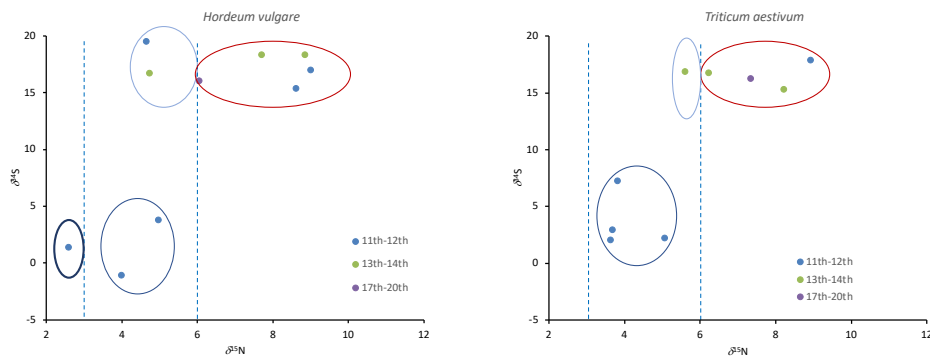


324
 325 Figure 6: Nitrogen, carbon and C/N ratios for the wheat (red bold circle) and barley (blue bold circles).
 326 The time axis is only indicative of the period spanning from the 11th to the 20th c.

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 $\Delta^{13}\text{C}$ 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: $\delta^{34}\text{S}$ values with respect to the $\delta^{15}\text{N}$ 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, $\delta^{13}\text{C}$: chi-squared = 1.2476, p-value = 0.583, $\delta^{15}\text{N}$: chi-squared
 351 = 2.4835, p-value = 0.345, $\delta^{34}\text{S}$: chi-squared = 2.2044, p-value = 0.413) and hulled barley
 352 (Kruskal Wallis tests, $\delta^{13}\text{C}$: chi-squared = 2.7036, p-value = 0.26, $\delta^{15}\text{N}$: chi-squared =
 353 1.0665, p-value = 0.616, $\delta^{34}\text{S}$: 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 $\delta^{15}\text{N}$, $\delta^{34}\text{S}$ and $\delta^{13}\text{C}$ 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)*

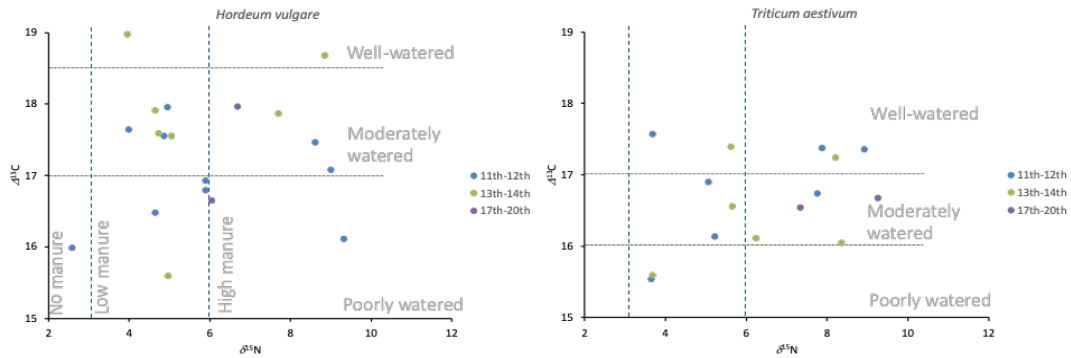
366 Founded around the tenth century, Aghmat underwent rapid development during the eleventh-
 367 twelfth centuries, experiencing strong economic growth. Samples from this period provide the
 368 earliest known archaeological evidence of the plant landscapes and productions of this region.
 369 At that 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

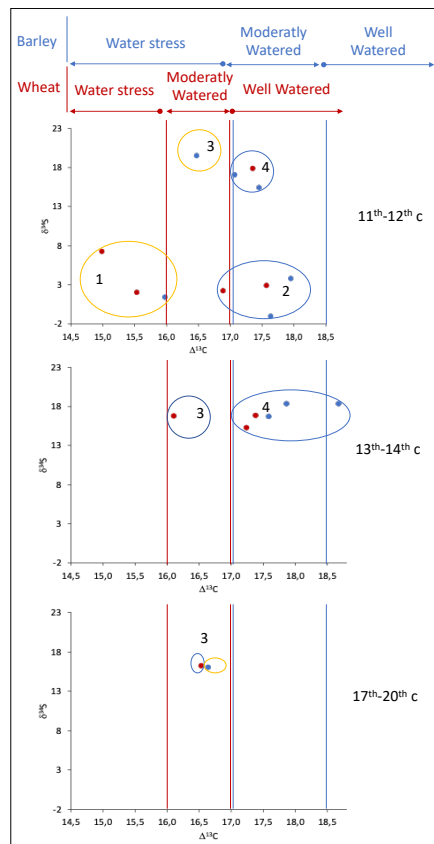


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431

432

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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576 Historiques du Maroc: Adaptations, Transformations - L'exemple de la région du Haouz".

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922 Appendix 2: Anthracological raw data from Aghmat.

Space	VIII	V	XXXXIII		XVI	XVI	XXXII	V-VI-VII		
Zone	Qubba	West Palace Garden	South Cistern		West Garden/Courtyard of	North House - North Corridor	Maison nord- Nord	Basin		
Relative dating	11th-12th c.	middle 12th c.-middle	14th c.-middle 14th	14th c.	14th c.	14th c.	early 16th c.	16th-17th c.		
¹⁴ C dating	930 ±30 BP	800 ±30 BP	645 ±30 BP					140 ±140 BP		
Stratigraphic unit	QUB 4204	PAL 1561	PAL 2361	PAL 1231	PAL 2049 A	PAL 2049B	PAL 2355	PAL 1523		
Type of context	Coal pocket within landfill/Séguia meadow fill	Charcoal pocket (from planting pit?) within garden stratum	Charcoal-rich level end: residual occupation? / discards? / colluvial deposits?	Palace courtyard pit	Charcoal pocket included in 2032 (Ash pocket in a destruction level/garden soil)	Silty pocket with large charcoal pieces beneath 2049A, included within 2032	Charcoal circulation level	Late reoccupation discards		
Sample volume (L)	5	9	2,5	-	4	5	1	7		
Taxon									Total number	Total %
<i>Acacia /Ficus</i>	2	-	-	-	1	-	-	-	3	0,2
<i>Anacardiaceae/cf. Pistacia</i>	-	-	-	5	3	1	1	-	10	0,7
<i>Arbutus</i>	-	-	-	-	-	1	-	-	1	0,1
<i>cf. Cistaceae/Ericaceae</i>	-	-	-	-	-	1	-	-	1	0,1
<i>Cistus</i>	-	-	-	-	-	-	1	-	1	0,1
<i>Ficus</i>	15	-	-	2	-	-	-	1	18	1,3
<i>Fraxinus</i>	23	-	5	-	35	9	1	3	76	5,6
<i>cf. Fraxinus</i>	2	-	1	-	2	-	-	-	5	0,4
<i>Monocotyledoneae</i>	17	1	-	-	40	13	4	-	74	5,4
<i>Olea europaea</i>	10	60	163	-	35	9	128	132	477	35,0
<i>cf. Olea europaea</i>	-	-	6	-	2	2	6	4	20	1,5
<i>Pistacia lentiscus</i>	-	-	-	3	-	1	-	1	5	0,4
<i>Populus /Salix</i>	8	-	-	-	25	24	-	2	59	4,3
<i>cf. Populus /Salix</i>	3	-	-	-	-	-	-	-	3	0,2
<i>Punica granatum</i>	22	1	-	-	-	-	6	1	29	2,1
<i>cf. Punica granatum</i>	-	-	-	-	1	-	2	-	3	0,2
<i>Quercus semp.</i>	10	-	-	136	4	4	44	1	199	14,6
<i>Quercus</i>	-	-	-	-	-	-	1	-	1	0,1
<i>Phillyrea /Rhamnus</i>	-	-	-	4	-	-	-	-	4	0,3
<i>Rosaceae Maloideae</i>	18	-	-	-	5	-	74	-	97	7,1
<i>cf. Rosaceae Maloideae</i>	-	-	-	-	-	1	-	-	1	0,1
<i>Rosaceae Prunoideae</i>	10	-	8	-	6	-	-	-	24	1,8
<i>cf. Rosaceae Prunoideae</i>	2	-	-	-	-	-	-	-	2	0,1
<i>Tamarix</i>	-	-	-	-	-	-	-	2	2	0,1
<i>Tetraclinis articulata</i>	25	-	-	-	31	51	-	1	108	7,9
<i>Vitis vinifera</i>	12	-	2	-	-	-	-	-	14	1,0
<i>Ziziphus</i>	-	-	-	-	-	-	-	1	1	0,1
Not determinable	3	-	1	-	-	-	1	-	5	0,4
Undetermined	18	-	14	-	10	9	5	1	57	4,2
Total number of studied fragments	200	63	200	150	200	200	200	150	1363	100,0
Bark	2	1	4	-	6	4	2	-	18	1,3
Node	9	2	2	2	2	1	1	1	21	1,5
Pith	11	2	3	21	5	3	7	5	52	3,8

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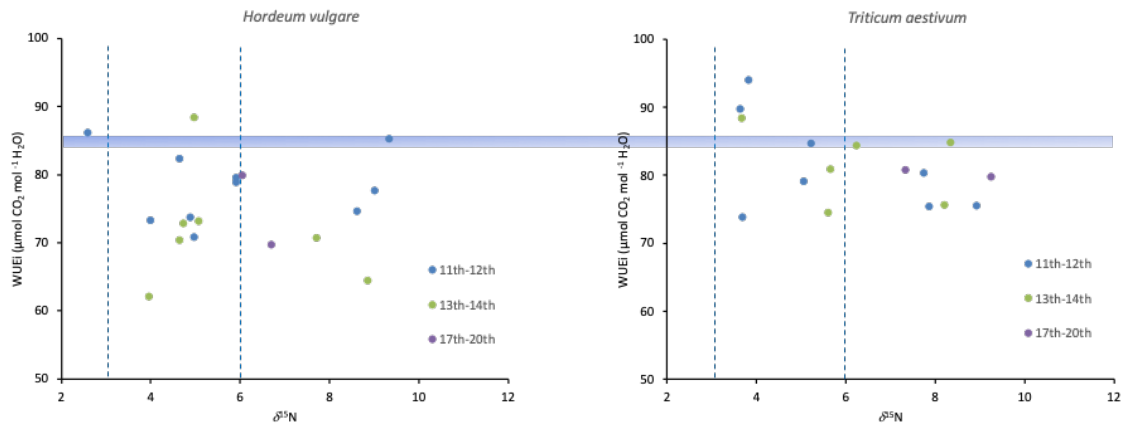
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925 Appendix 3: Isotopic raw data from Aghmat.

Archaeological site	Taxa	Sector	SU	Age	Archaeological type remains	Lab Ref	Number of remains	Weight (mg)	δ ¹³ C (‰) corrected	Presip (mm) during grain filling Darman &	N (%)	δ ¹⁵ N (‰) corrected	C (%)	pCO ₂ ppm (Law Dome GMAP 2006)	δ ¹³ C _{org} (‰) (Farquhar et al., 1989)	Δ ¹³ C	WUEI (μmol CO ₂ mol ⁻¹ H ₂ O)	Annual precip (mm)	δ ¹³ S _{SO₄} corrected	S (%)	C/N	
Aghmat (541 m.a.s.l)	<i>Hordeum vulgare</i>	QUB	4204	11th-12th	caryopse	JR19	1	30,17	4,3	158	1,1	-22,5	33,0	283	-6,4	16,5		82,3	71	19,5	0,5	28,8
						JR20	1	14,57	8,3	45	1,4	-23,5	33,7	283	-6,4	17,5	74,7	136	15,4	0,2	23,5	
						JR21	1	12,63	8,7	40	2,1	-23,1	34,7	283	-6,4	17,1	77,7	106	17,0	0,3	16,8	
						JR22	1	8,52	9,0	36	2,4	-22,2	34,5	283	-6,4	16,1	85,2	56			22,3	
						JR23	1	17,45	4,7	143	1,7	-24,0	39,4	283	-6,4	18,0	70,8	188	3,8	0,1	22,9	
						JR24	1	26,11	2,3	300	0,9	-22,1	19,4	283	-6,4	16,0	86,2	52	1,4	0,0	19,7	
						JR25	1	12,6	5,6	106	1,5	-23,0	41,0	283	-6,4	16,9	78,9	96			27,4	
						JR26	1	14,52	3,7	194	1,3	-23,7	28,2	283	-6,4	17,6	73,2	153	-1,1	0,1	22,6	
						JR28	1	8,37	5,6	106	2,0	-22,8	29,4	282	-6,4	16,8	79,5	88			19,8	
						JR39	1	9,26	4,6	147	1,5	-23,6	45,7	282	-6,4	17,6	73,7	145			31,1	
						JR47	1	14,89	7,4	61	1,8	-23,8	40,5	280	-6,4	17,9	70,7	178	18,3	0,2	22,2	
						JR48	1	7,37	4,3	158	2,2	-23,9	50,9	280	-6,4	17,9	70,4	183			23,2	
		JR49	1	14,33	4,4	154	2,0	-23,6	43,1	280	-6,4	17,6	73,9	148	16,7	0,2	21,4					
		JR58	1	9,63	4,7	143	2,3	-21,6	49,8	280	-6,4	15,6	88,4	40			22,1					
		JR59	1	5,61	4,8	138	2,4	-23,5	58,8	280	-6,4	17,6	73,2	145			24,3					
		JR60	1	10,5				-23,6	51,8	280	-6,4	17,7	72,3	156								
		JR61	1	14,02	8,6	42	1,8	-24,6	43,3	280	-6,4	18,7	64,5	303	18,3	0,5	26,9					
		JR62	1	11,91	3,7	196	1,7	-24,9	49,6	280	-6,4	19,0	62,2	369			28,7					
		JR79	1	8,51																		
		JR80	1	7,46																		
		JR81	1	9,39																		
		JR82	1	22,05	5,7	102	2,5	-22,6	49,3	279	-6,3	16,6	79,9	80	16,1	0,2	19,4					
		JR83	1	8,17	6,4	83	2,4	-23,9	56,7	279	-6,3	18,0	68,8	189			24,1					
		Mean 11th - 12th c						5,7	128	1,6	-23,0	36,8	283	-6,4	17,0	78,2	109	9,8	0,2	23,5		
		SD 11th-12th c						2,3	81	0,5	0,6	3,9	0,0	0,7	5,2	4,5	9,0	0,2	4,4			
		Mean 14th-16th						5,4	127	2,0	-23,7	48,5	280	-6,4	17,7	71,8	190	17,3	0,3	24,1		
		SD 14th-16th						1,8	55	0,3	1,0	5,9	0,0	1,0	7,8	10,2	0,9	0,2	2,7			
		Mean 17th-20th c						6,1	92	2,4	-23,2	53,0	279	-6,3	17,3	74,8	135	16,1	0,2	21,7		
		SD 17th-20th c						0,5	19	0,1	0,3	5,2	0,0	0,9	7,2	7,7			3,3			
		Triticum aestivum/durum	QUB	4204	11th-12th	caryopse	JR27	1	10,65			1,9	-22,8	42,6	283	-6,4	16,7	80,4	102			22,5
							JR28	1	18,44				-23,5	16,4	283	-6,4	17,5	74,3	158			
							JR29	1	15,15	3,3	216	2,9	-21,6	41,1	283	-6,4	15,5	89,7	52	2,0	0,1	14,3
							JR30	1	6,8	7,6	57	2,0	-23,4	47,1	283	-6,4	17,4	75,4	146			23,5
							JR31	1	12,11	8,6	41	1,8	-23,4	37,6	283	-6,4	17,4	75,5	145	17,8	0,2	21,2
							JR32	1	16,6	3,4	213	1,4	-23,6	23,9	283	-6,4	17,6	73,8	163	2,9	0,1	17,0
							JR33	1	16,85	3,5	204	1,6	-21,1	32,3	283	-6,4	15,0	94,0	38	7,2	0,1	20,0
							JR34	1	18,78	4,8	138	0,9	-22,9	14,6	283	-6,4	16,9	79,1	112	2,2	0,0	16,1
							JR40	1	7,1	4,9	132	2,8	-22,2	44,2	282	-6,4	16,1	84,7	73			15,6
							JR50	1	4,77	8,0	49	2,1	-22,1	37,7	280	-6,4	16,0	84,8	69			17,9
							JR63	1	13,92	5,3	117	2,8	-23,3	47,8	280	-6,4	17,4	74,4	147	16,9	0,3	17,1
							JR64	1	12,24	7,9	52	3,2	-23,2	47,2	280	-6,4	17,2	75,6	136	15,3	0,3	14,6
							JR65	1	8,73	3,4	214	2,3	-21,6	55,6	280	-6,4	15,6	88,4	44			24,7
							JR66	1	10,86	5,3	115	3,3	-22,5	52,0	280	-6,4	16,6	80,9	92			15,8
							JR67	1	14,97	5,9	96	3,2	-22,1	52,7	280	-6,4	16,1	84,4	72	16,8	0,3	16,2
							JR84	1	7,89	8,9	37	3,7	-22,6	50,6	279	-6,3	16,7	79,7	98			13,8
JR85	1						19,81	7,0	68	4,7	-22,5	48,4	279	-6,3	16,5	80,7	91	16,2	0,2	10,2		
Mean 11th - 12th c											5,4	133	1,9	-22,7	33,3	283	-6,4	16,7	80,8	110	6,4	0,1
SD 11th-12th c						2,1	74	0,7	0,9	12,2	0,0	0,9	7,3	4,7	6,7	0,1	3,5					
Mean 14th-16th						6,0	107	2,8	-23,5	48,8	280	-6,4	16,5	81,4	95	16,3	0,3	17,7				
SD 14th-16th						1,8	60	0,5	0,7	6,3	0,0	0,7	5,3	38	0,9	0,0	3,6					
Mean 17th-20th c						8,0	53	4,2	-22,6	49,5	279	-6,3	16,8	80,2	95	16,2	0,2	12,0				
SD 17th-20th c																						

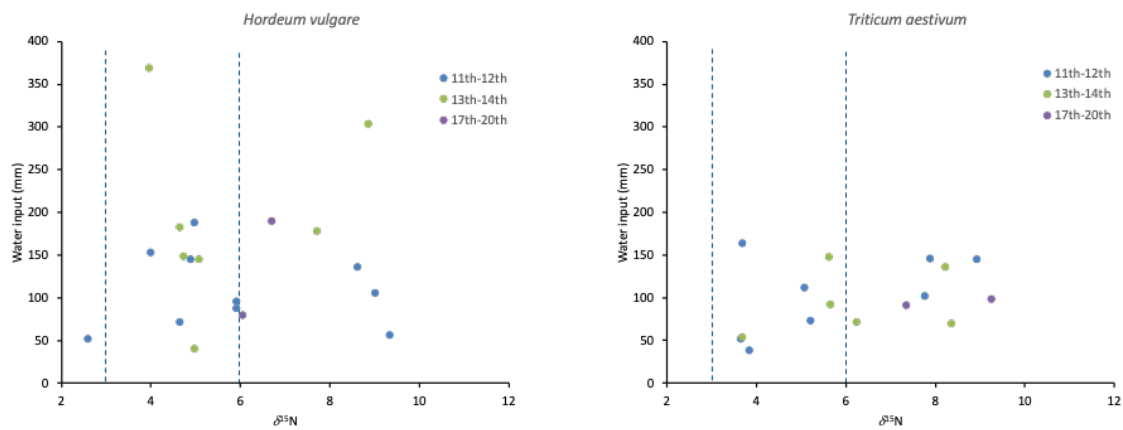
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Appendix 4: Water use efficiency against $\delta^{15}\text{N}$ of both barley (left panel) and wheat (right panel). The blue line represents the reference limit of hydric stress ($> 85 \mu\text{m}$)



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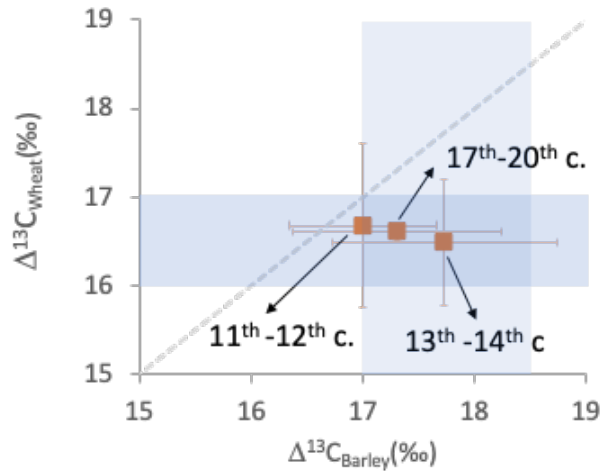
Appendix 5: Water input during cereal filling (mm) against $\delta^{15}\text{N}$ of both barley (left panel) and wheat (right panel)



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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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