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1 Crop manuring on the Beauce plateau (France) during the Second Iron Age

2

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24 **Abstract**

25 The studied area on the Beauce plateau (France) was densely inhabited during the Iron Age and
26 several archaeological excavations have enriched our knowledge of agrarian systems during this
27 period. This study investigates fertilisation management between 400 and 80 BCE focusing on
28 numerous crop storage remains from three neighbouring farms. We sampled 18 cereal groups with
29 50 grains to conduct stable carbon and nitrogen isotope analyses commonly used for reconstructing
30 past agricultural practices, in particular $\delta^{15}\text{N}$ as a proxy for manuring.

31 The $\delta^{15}\text{N}$ values range between 1.3‰ and 7.6‰, with an increase over time from 3.2‰ to 5.6‰
32 (mean by occupation phase), reflecting a continuous use of manure, consistent with the dynamism of
33 agricultural activities during the Second Iron Age. All three farms seem to have applied the same
34 manuring strategies. Barley and emmer may have been manured more often than free-threshing
35 wheats, even when free-threshing wheats are the dominant crop. This contrasts with the
36 neighbouring Ile-de-France region and indicates diversity in agropastoral systems between regions.
37 The analysis of several grain groups from the same silo shows diversified $\delta^{15}\text{N}$ values between crops,
38 reflecting various manuring rates: some fields were fertilised while others were less so. This is
39 consistent with the description of a large-scale farming system, with a large cultivated area and a
40 mosaic landscape.

41

42 Keywords: Manuring, Crop stable isotopes, Rural settlements, Iron Age

43 1. Introduction

44 1.1. Research context

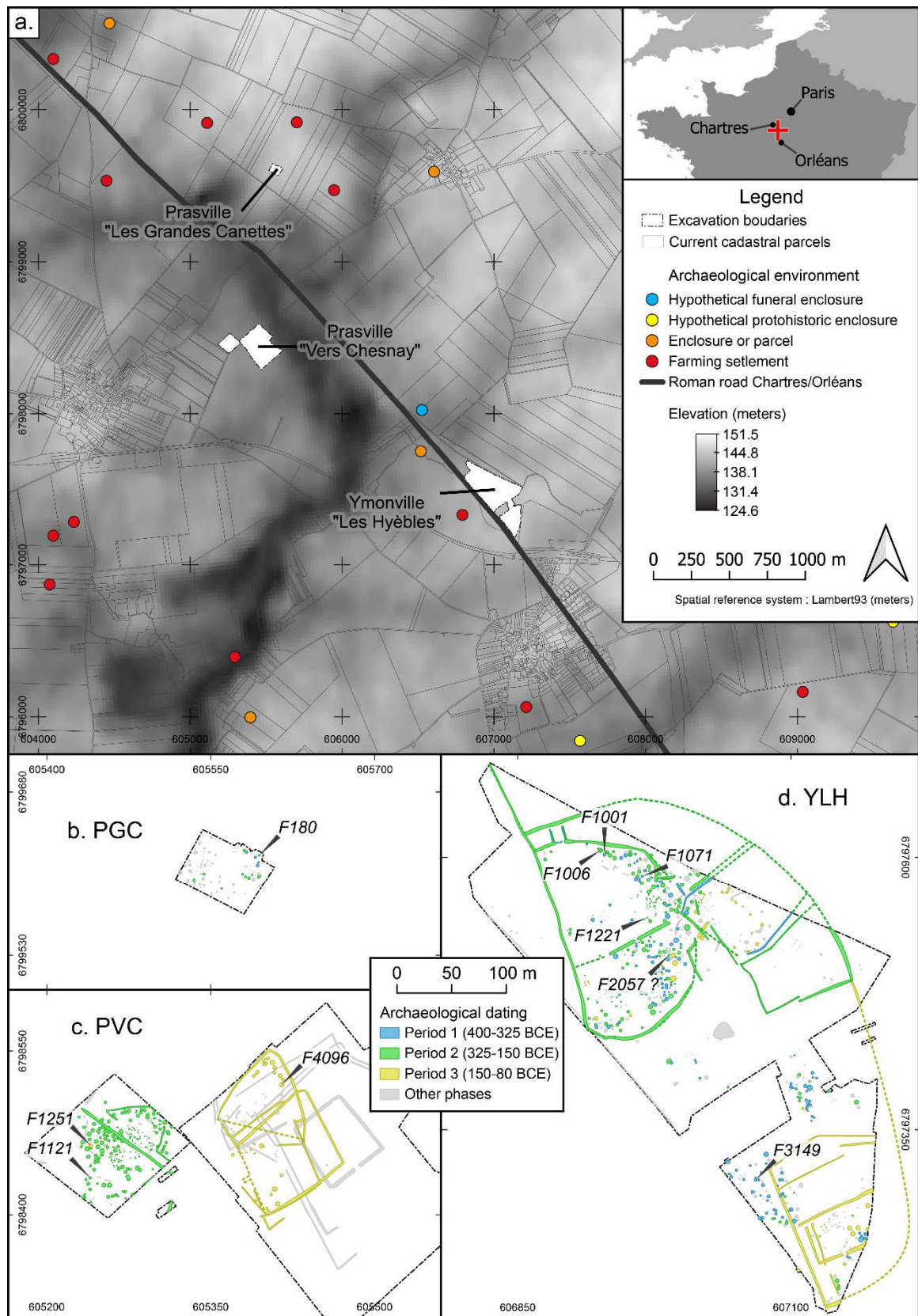
45 Agricultural productions during the Second Iron Age are relatively well known in the northern half of
46 France (Zech-Matterne *et al.*, 2013, Malrain *et al.*, 2018). In earlier periods, crops were diversified and
47 appear to have been cultivated at the household level. Changes occurred during the Second Iron Age
48 with a reorganisation of agricultural practices to increase production. Through the study of
49 archaeological weed ecology, an extensification of cropping systems can be claimed in some regions
50 (Normandie, Picardie, Île-de-France and Champagne) (Zech-Matterne and Brun, 2016). The
51 occurrence of nitrophilous weeds (75 out of 211 taxa) combined with crops suggests the
52 maintenance of soil fertility for several centuries, possibly through crop rotation, grass or tilled
53 fallow, farmyard manure, penning livestock on the fallows or in fields during intercrop periods (Zech-
54 Matterne *et al.*, 2018). In north-western France, the increase in pulses may indicate a cereal-legume
55 rotation (Neveu *et al.*, 2021). This technique slows down soil depletion and reduces amendment
56 rates. In north-eastern France, farm production was less diversified and specialized in the culture of
57 one or two cereals (Zech-Matterne *et al.*, 2013, 2014). Fertility maintenance must thus have involved
58 other solutions than legume rotations. However, the weed ecology approach cannot identify the
59 (natural or anthropic) origin of soil fertility.

60 Characterising fertilisation practices enhances our understanding of (more or less intensive or
61 extensive) cereal production modes, impacting crop yields, labour force, labour productivity and land
62 use. In intensive cropping systems, a large amount of labour is invested per unit area to ensure good
63 crop growth, which allows high yields (Morrison 1994). The choice of an extensive cropping system
64 affects the use of manure: manure is supposed to be spread more heterogeneously across the
65 numerous farmland fields than in intensive agriculture. Manure inputs involves livestock
66 management and collection, storage and transport of dung. Moreover, fertility management was not
67 necessarily homogeneous from one territory to another, depending on environmental constraints
68 and farmers' or owners' choices. We therefore consider the interest of detecting these practices on a
69 finer scale than the weed ecology studies described above. In this study, fertilisation practices were
70 investigated in three neighbouring farms from the Second Iron Age in the Centre region of France,
71 using biogeochemical analysis of crop remains, a methodology proven to be suitable for exploring
72 past soil fertility (Bogaard *et al.*, 2007, 2013; Fraser *et al.*, 2011).

73 1.2. Description of the sites

74 The farms are located on the Beauce plateau within 2 km of each other, halfway between Chartres
75 and Orléans (Figure 1). Aerial surveys and trial trenching have shown that the surrounding land was
76 densely inhabited during the Iron Age, with a predominance of enclosed rural settlements during the
77 Second Iron Age. The Roman Chartres-Orléans Road, probably of protohistoric origin, runs between
78 the studied sites and highlights their inclusion in a wider network of agricultural settlements, with
79 likely interdependent relationships between farms (Malrain, 2020).

80 The Beauce plateau, in the Paris Basin, is an area of limestone outcrops, covered with fertile silts. The
81 topography is not very contrasted. Valley bottoms are currently dry, but they were probably formerly
82 wet and wooded. The dry and deforested plateaus hosted grasslands and crops. The farms are
83 located on plateaus, close to slopes, at the interface between these two environments (Cousot,
84 2010; Martin, 2010; Pradat, 2010).



85

86 *Figure 1. Location of the sites in their archaeological environment (a) and phased plans of Prasville*
 87 *“Les Grandes Canettes” (b), Prasville “Vers Chesnay” (c) and Ymonville “Les Hyèbles” (d). The sampled*
 88 *structures are shown on the plans. Data: Yvernaut, 2010; Bailleux, 2010; Lusson, 2011; Josset, 2012;*
 89 *IGN BD Parcellaire 2020; EAA EU-DEM 2020.*

90 At the intermediate-sized farm of Prasville “Vers Chesnay” (Bailleux, 2010), five building phases
91 between 325 BCE and 300 CE have been identified. During phases 1 and 2 (325/150 BCE), a silo
92 cluster organised around small post-mounted buildings provided good storage capacity. Some small
93 ditches mark the early stages of structuring the habitat. From 200 BCE onwards, the settlement
94 extended over a larger area while building size also increased, and large ditches were established,
95 forming an open enclosure. The settlement comprised agricultural and craft activities: inhabitants
96 bred Caprinae and cultivated mainly free-threshing wheats (45% of food plant remains) and emmer
97 (45%). The other food plant species are rare. In the third phase (150/80 BCE), the habitat moved
98 150 m to the east, with no chronological hiatus, and three successive ditched enclosures were
99 constructed. Emmer became the main cultivated crop (74%). Cattle and horses were raised. From the
100 following phases onwards, the architecture became monumental and during the Roman Empire,
101 production focused on cattle breeding.

102 The excavation of Prasville “Les Grandes Canettes” (Lusson, 2011) was carried out over a small
103 surface, on the edge of a smaller farm. Little is known of spatial organisation, as the habitat
104 continues northwards, outside the excavation limits. The site is mainly characterised by the presence
105 of silos and pits and no ditches structuring the space were observed. Two phases were identified
106 (400/300 BCE and 325/250 BCE) with agricultural activities focusing on emmer cultivation (73% of
107 food plant remains) and pig and caprine husbandry. Millet cultivation was secondary (11%) and some
108 cattle were also raised.

109 Ymonville “Les Hyèbles” (Josset, 2012) was intensively settled between its foundation in the
110 sixth/fifth centuries and its abandonment in the first century BCE. The settlement was an aristocratic
111 farm. Phases 2 (500/325 BCE) and 3 (325/150 BCE) correspond to the establishment of the
112 occupation centred around two founding graves. A large D-shaped enclosure was installed,
113 encompassed by a wider one. The main D-shaped enclosure comprised a building facing an empty
114 area (potentially a public place), surrounded by trophies exhibition posts and numerous silos.
115 Multiple activities were carried out: crafting (metallurgy, leather working, weaving and milling),
116 husbandry, cereal cropping (mainly free-threshing wheats – 61% – and secondarily barley – 26%) and
117 social events (trophies exhibition and assemblies). This was thus a dual-purpose settlement
118 (agriculture and sanctuary). During phase 4 (150/50 BCE), the initial settlement was still occupied,
119 but a new centre was built 100 m to the south. A new residential building was enclosed by a large
120 quadrangular ditch. The last settlement phase dates from the end of the first century BCE and
121 corresponds to the abandonment of enclosures and the digging of a Roman limestone quarry.

122 1.3. The use of stable nitrogen isotope values in highlighting soil fertility management

123 Cereals take up nitrogen from the soil, largely derived from the decomposition of organic matter by
124 microorganisms. These processes of transformation of organic nitrogen into bioavailable mineral
125 forms lead to different isotopic compositions, subject to many environmental factors, such as
126 rainfall, temperature, soil depth, topographic position, and the overall nature of the parent material
127 (Amundson *et al.*, 2003; Högberg, 1997). The anthropogenic history of the soil and agricultural
128 activities are also important factors in stable nitrogen isotope ratio variation ($\delta^{15}\text{N}$).

129 From the 1970s onwards, ecologists and agronomists noticed that $\delta^{15}\text{N}$ values in soil increase with
130 the application of farmyard manure (Riga *et al.*, 1971; Choi *et al.*, 2003; Bol *et al.*, 2005). During
131 storage and composting, animal manure loses part of its nitrogen, preferentially the lighter ^{14}N
132 isotope, through ammonia volatilization, leading to significant relative enrichment in the heavier ^{15}N
133 isotope (Högberg, 1997; Szpak, 2014). The application of manure thus causes relative ^{15}N -enrichment
134 in soil and plants. When charred under temperatures between $\sim 215\text{-}260^\circ\text{C}$ (i.e. the charring window

135 for preservation of grain morphology; Charles *et al.*, 2015), charred plant remains are likely to
136 preserve their in vivo $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (DeNiro and Hastorf, 1985; Nitsch *et al.*, 2015) and is
137 currently used to investigate manuring in archaeological contexts (Bogaard *et al.*, 2007, 2013;
138 Aguilera *et al.*, 2008; Fraser *et al.*, 2011; Kanstrup *et al.*, 2011).

139 Long-term experiments conducted in temperate Europe have shown that plants growing in a poorly
140 anthropized environment, or in plots that have not been manured for a long time, generally have
141 $\delta^{15}\text{N}$ values below 3‰. Values above this threshold refer to plants grown on soils enriched in ^{15}N by a
142 high concentration of organic matter, deriving from natural conditions or human activities. Above
143 6‰, $\delta^{15}\text{N}$ values would reflect high manuring rates (*e.g.*, 25-35 t/ha) in the long term (Fraser *et al.*,
144 2011; Bogaard *et al.*, 2013). For other regions, further experiments were conducted to define locally
145 adapted thresholds (Larsson *et al.*, 2019). The manuring effect can be detected as early as the first
146 year after manure application (Fraser *et al.*, 2011). Manuring rates and application frequency affect
147 the manuring effect on $\delta^{15}\text{N}$ values: ^{15}N -enrichment is greater the more a plot is fertilised in quantity
148 and over time. After the cessation of fertilisation, $\delta^{15}\text{N}$ values gradually decrease. Measurements of
149 intermediate $\delta^{15}\text{N}$ values could indicate either abundant recent fertilisation, medium fertilisation
150 over the long term or the residues of long-term fertilisation abandoned some time ago. Very high
151 $\delta^{15}\text{N}$ values (over 7-9‰) indicate intensive management practices, with high manuring rates
152 comparable to those applied in garden agriculture.

153 Other agricultural practices may affect the $\delta^{15}\text{N}$ values of the soil and plant (Szpak, 2014). Clearing
154 lands by burning them alters the nitrogen cycle and leads to an increase in $\delta^{15}\text{N}$ values, through
155 various complex processes with impacts that can last for several years or even decades. Tillage brings
156 formerly mineralised nutrients to the soil surface, but its influence on crop $\delta^{15}\text{N}$ values is unlikely
157 (Selles *et al.*, 2011). Other fertilisation techniques, such as cereal-legume rotation combined with
158 green manure (a legume crop voluntarily cut and buried in the ground), decrease $\delta^{15}\text{N}$ values in soil
159 (Riga *et al.*, 1971) and probably those of the following crops. For this reason, it may be difficult to
160 differentiate cereals cultivated after legumes from cereals grown without manuring. Further
161 experiments are needed to understand the impact of legumes cultivation on soil $\delta^{15}\text{N}$ values.

162 In order to measure a baseline for $\delta^{15}\text{N}$ values of unfertilised flora, we use the deer bone collagen
163 proxy (Bogaard *et al.*, 2013). Wild fauna is very rare in Second Iron Age sites and only $\delta^{15}\text{N}$ values
164 from 20 deer bone were published for the early Roman sites of Jouars-Pontchartrain “La Ferme
165 d’Ithe” (n=10, range: 3.1–6.1‰) and Palaiseau “Les Trois Mares” (n=10, range: 4.9–6.5‰), localised
166 60km north-east of the three Beauce farms, also in the south-western Paris Basin (Aguilera *et al.*,
167 2018). The mean of the $\delta^{15}\text{N}$ values is 5.0 ± 1.0 ‰ (Supplementary Material 1). After subtracting a 3‰
168 value for the trophic level shift (Caut *et al.*, 2009), the $\delta^{15}\text{N}$ values of the deer diet can be estimated
169 to 2.0 ± 1.0 ‰. As discussed in Styring *et al.* (2017), $\delta^{15}\text{N}$ values above mean+1 standard deviation of
170 deer diet could be interpreted as ^{15}N -enriched with respect to non-anthropogenic flora. According to
171 these local deer samples, the local baseline for $\delta^{15}\text{N}$ values of unfertilised flora is 3.0‰, similar to the
172 3‰-threshold established by long-term manuring experiments in others parts of temperate Europe
173 (Fraser *et al.*, 2011).

174 1.4. Objectives and hypothesis

175 Dense land use in the area and high storage capacity (numerous silos) during the whole Second Iron
176 Age illustrate the dynamism of agricultural production, alongside other activities, reflecting the
177 transformation of protohistoric society (Malrain *et al.*, 2018). The development and enrichment of
178 rural settlements during the Second Iron Age relied heavily on agricultural profits, which in turn
179 depended on fertilisation techniques for increasing yields. Here, we investigate manure fertilisation

180 and variations in manuring, depending on the cereals, production units and time periods. The
181 sampling protocol was adapted in a way to approach these different spatiotemporal scales.
182 Production modes are compared across three neighbouring farms, over several centuries of
183 occupation, but also within the same storage structure, in order to detect fine variations between
184 fields.

185 We assume that if Second Iron Age farmers used manure to increase yields, then this practice should
186 be reflected in the nitrogen isotopic composition of cereals. In an extensive farming system, the
187 cultivated area is large and manure spreading cannot reasonably be uniform across all fields.
188 Variations in cereal $\delta^{15}\text{N}$ values are expected. Some species may have been favoured over others,
189 and would have received more manure.

190 2. Material and methods

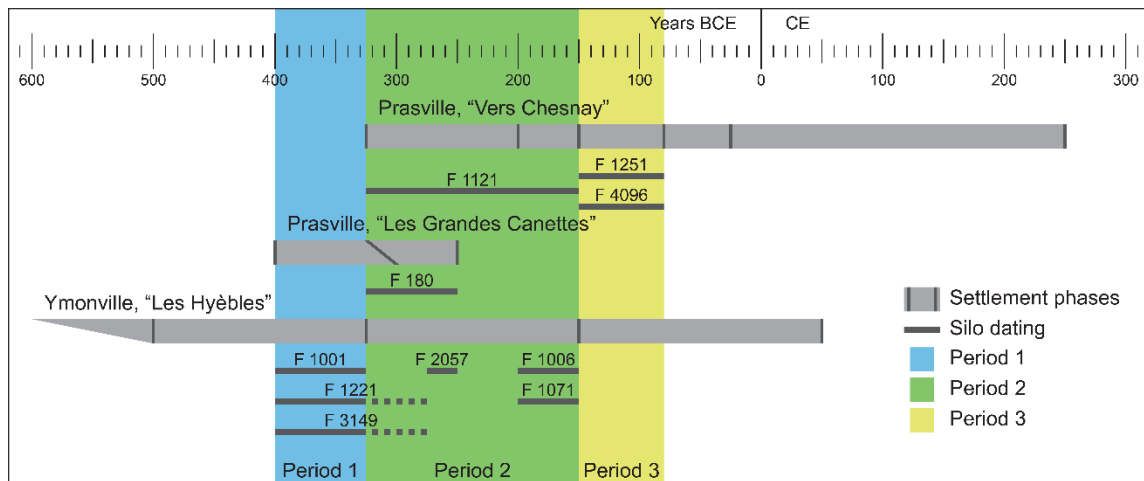
191 2.1. Sample selection and preparation

192 Samples were obtained from detrital deposits with a high density of charred grains. These
193 concentrations consist of aggregate cereal grains, dominated by one or two taxa, and weed seeds,
194 charred and eliminated at the same time, and most probably harvested in the same year or at most a
195 few years apart. We selected the three dominant taxa of the sites: hulled barley (*Hordeum vulgare*),
196 free-threshing wheats (*Triticum aestivum* ssp. *aestivum*/*T. turgidum* ssp. *durum*/*T. turgidum* ssp.
197 *turgidum* group) and emmer wheat (*Triticum turgidum* ssp. *dicoccum*). Fifty grains of the same taxon
198 (herein “one grain group”) were collected from each archaeobotanical deposit to accurately reflect
199 crop values at the field scale. The grain group is subdivided into five samples composed of 10 grains
200 each to reflect part of intra-field variability, which can be significant within a single plot (Bogaard *et*
201 *al.*, 2007; Larsson *et al.*, 2019). A total of 18 grain groups were studied (90 samples with a total of 900
202 grains).

203 Archaeological events at the sites have been relatively dated on the basis of artefacts. The sampled
204 structures can be grouped into three consistent periods between the three farms (Figure 2 and Table
205 1):

- 206 - Period 1 (400/325 BCE): silos F1001, F1221 and F3149 are from phase 2 of Ymonville “Les
207 Hyèbles”. This is the period during which Second Iron Age farms were installed in this area.
208 We sampled six grain groups for this period.
- 209 - Period 2 (325/150 BCE): silos F180 (phase 2 of Prasville “Les Grandes Canettes”), F1121
210 (phase 1-2 of Prasville “Vers Chesnay”), F1006, F1071 and F2057 (phase 3 of Ymonville “Les
211 Hyèbles”) correspond to a period of continuity or even increasing storage capacity with the
212 creation of the Prasville “Vers Chesnay” farm. Eight grain groups were obtained from these
213 silos.
- 214 - Period 3 (150/80 BCE): silos F1251 and F4096 (four grain group) belong to phase 3 of Prasville
215 “Vers Chesnay”. This phase corresponds to the relocation and creation of an establishment in
216 Prasville “Vers Chesnay” and Ymonville “Les Hyèbles”, reflecting new dynamics in rural
217 habitat management.

218 The grains were cleaned of sedimentary concretions and roots by gently scraping under a
219 stereomicroscope. In order to remove soil contaminants (mainly carbonates in this calcareous
220 region), samples were treated with a gentle acid treatment (adapted from Vaiglova *et al.*, 2014;
221 Aguilera *et al.*, 2018): 10 whole grains were treated in 10 mL of a solution of 0.5 M HCl for 1 h at
222 70° C, soaked in distilled water at room temperature with water changed after 24h, 8h and 16h,
223 freeze-dried and milled to a fine powder with an agate pestle and mortar.



224

225 *Figure 2. Silo dating and site periodisation.*

226

227 2.2. Isotopic analyses

228 Measurements were performed on 1 mg of grain powder in an elemental analyser (Thermo Flash
 229 2000), interfaced with an isotope mass spectrometer (Thermo DeltaV Advantage), at the Muséum
 230 national d’Histoire naturelle (Paris, France). Stable isotope ratios measurement results are expressed
 231 using $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values (‰), relative to atmospheric N_2 and the VPDB standard, respectively. The
 232 precision and accuracy of analyses are determined using a laboratory standard (alanine) normalized
 233 to the IAEA-600 caffeine international standard, and a peach leaf standard (NIST SRM 1547). Over the
 234 course of all analyses, the alanine standard (n = 24) gave mean values of $0.72 \pm 0.13\text{‰}$ for $\delta^{15}\text{N}$
 235 (expected value = 0.60‰), $-21.82 \pm 0.13\text{‰}$ for $\delta^{13}\text{C}$ (expected value = -22.17‰), and $40.50 \pm 0.29\%$
 236 for C content (expected value = 40.44%) and the peach leaf standard (n = 21) gave mean values of
 237 $2.87 \pm 0.05\%$ for N content (expected value = 2.97%). Analytical precision, determined within each
 238 run from eight alanine analyses, varied between $\pm 0.06\text{‰}$ and $\pm 0.16\text{‰}$ for $\delta^{13}\text{C}$; $\pm 0.09\text{‰}$ and
 239 $\pm 0.17\text{‰}$ for $\delta^{15}\text{N}$; $\pm 0.15\%$ and $\pm 0.30\%$ for C content. For the N content, analytical precision,
 240 determined from seven peach leaf analyses, ranges from $\pm 0.02\%$ to $\pm 0.04\%$.

241 Following the arguments of Nitsch *et al.* (2015), who recommend considering an offset of 0.31‰ for
 242 $\delta^{15}\text{N}$ and 0.11‰ for $\delta^{13}\text{C}$ for the charring effect, the measured values were corrected. Other studies
 243 also show a charring effect (Fraser *et al.*, 2013; Styring *et al.*, 2013), and although some did not
 244 (Aguilera *et al.*, 2008; Kanstrup *et al.*, 2012; Szpak and Chiou, 2019), the correction is necessary when
 245 comparing cereal $\delta^{15}\text{N}$ values to deer diet $\delta^{15}\text{N}$ baseline (Nitsch *et al.*, 2015).

246 The results for $\delta^{13}\text{C}$ values are given and discussed in Supplementary Material 2, since we do not
 247 interpret them in terms of agricultural practices.

248 2.3. Statistical analyses

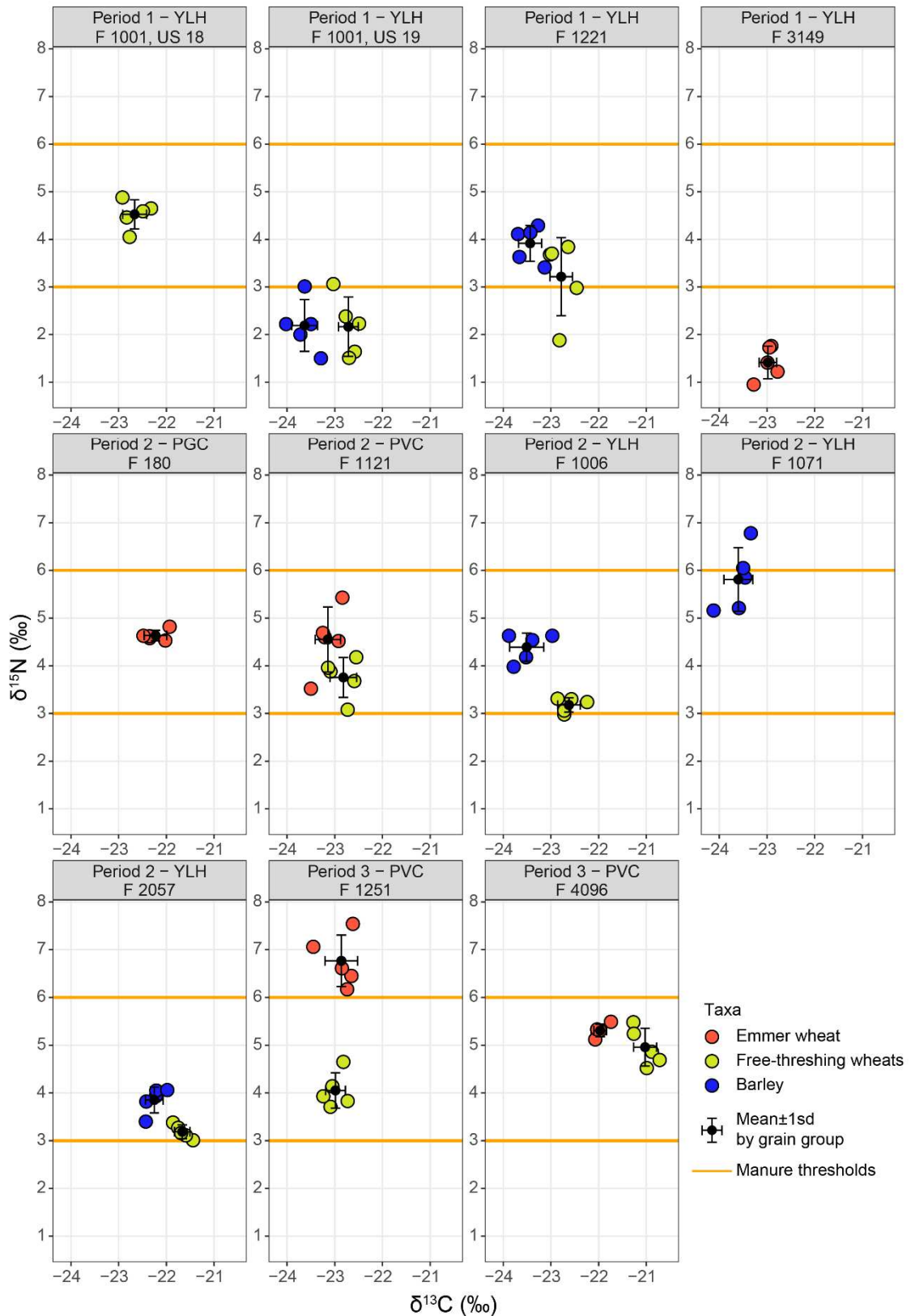
249 In order to understand variations in $\delta^{15}\text{N}$ measurements, a linear mixed-effects model was
 250 calculated, with the taxon and period as fixed effects (independent variables) and cereal grain group
 251 as a random effect. We use a mixed model because samples from the same grain group are
 252 correlated, and considered to be repeated measurements from the same deposit. Grain groups are
 253 compared two by two with the non-parametric Wilcoxon rank-sum test. All statistical tests and
 254 models are evaluated at an alpha level of 10%.

255 Statistical analyses were carried out using the statistical programming language R 4.0.2 (R Core Team,
256 2020). Models and their pseudo-R² were calculated with the nlme and the piecewiseSEM packages
257 (Pinheiro *et al.*, 2021; Lefcheck, 2016). Graphics were produced with the ggplot2 package (Wickham,
258 2016).

259 **3. Results**

260 Results from stable isotope analyses are shown in the Supplementary Material 3. Figure 3 shows $\delta^{15}\text{N}$
261 and $\delta^{13}\text{C}$ values for each sample (10 grains each), grouped by archaeological features. All grain
262 groups are clearly distinguished from each other on the basis of combined $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values, even
263 when they were retrieved from the same silo. Moreover, variability within each grain group is low
264 (standard deviation within a grain group is on average 0.4‰ for $\delta^{15}\text{N}$ and 0.2‰ for $\delta^{13}\text{C}$). This
265 suggests limited alteration of the grains' original stable isotope ratios by diagenesis. Summarized
266 data for each grain group are shown in Table 1 and in Figure 4. Overall, $\delta^{15}\text{N}$ values range between
267 1.0‰ (emmer wheat in silo F3149) and 7.5‰ (emmer wheat in silo F1251).

268 Overall, $\delta^{15}\text{N}$ values of the three taxa overlap, due to their wide range of variation. $\delta^{15}\text{N}$ values
269 increase from one period to the next, on average +1.2‰ at each step, visible in Figure 4 (mean [90%
270 CI] for Period 1: 2.9‰ [2.5; 3.3]; Period 2: 4.2‰ [3.9; 4.4]; Period 3: 5.3‰ [4.9; 5.7]). Linear mixed-
271 effects models have been calculated to verify these observations (Table 2).



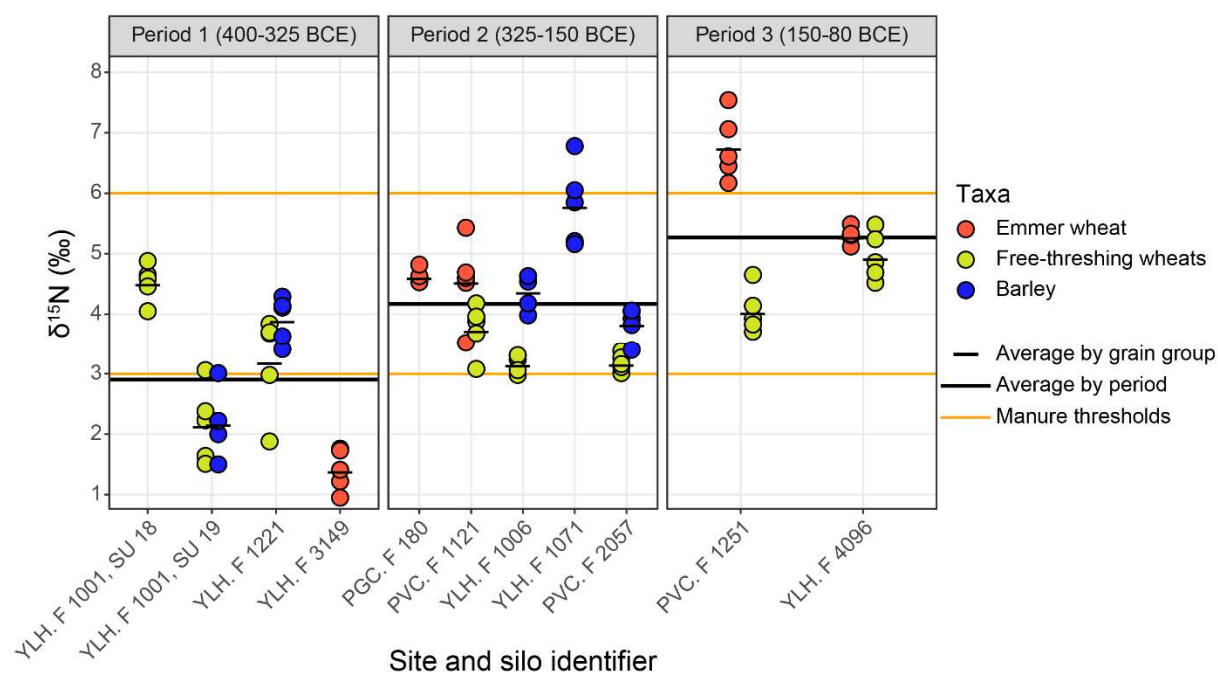
272

273 *Figure 3. Plot of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ of archaeological grains, grouped by archaeobotanical deposit. Each*
 274 *point is one sample of 10 grains. The black dots and crosses show the mean and 1 standard deviation*
 275 *for each grain group. Orange lines ($\delta^{15}\text{N}$): thresholds for manuring rates after Fraser et al. 2011 and*
 276 *Bogaard et al. 2013 (below 3‰, no manuring; 3-6‰, moderate or ancient manuring; above 6‰, high*
 277 *manuring rates).*

Id Site	Silo	Date	Period	Taxon	n	$\delta^{15}\text{N}$ (mean \pm 1sd)	$\delta^{13}\text{C}$ (mean \pm 1sd)
YLH	F 1001, SU 18	400-325 BCE	Period 1	Free-threshing wheats	5	4.5 \pm 0.3	-22.7 \pm 0.3
YLH	F 1001, SU 19	400-325 BCE	Period 1	Barley	5	2.2 \pm 0.5	-23.6 \pm 0.3
YLH	F 1001, SU 19	400-325 BCE	Period 1	Free-threshing wheats	5	2.2 \pm 0.6	-22.7 \pm 0.2
YLH	F 1221	400-275 BCE	Period 1	Barley	5	3.9 \pm 0.4	-23.4 \pm 0.2
YLH	F 1221	400-275 BCE	Period 1	Free-threshing wheats	5	3.2 \pm 0.8	-22.8 \pm 0.2
YLH	F 3149	400-275 BCE	Period 1	Emmer	5	1.4 \pm 0.3	-23.0 \pm 0.2
PGC	F 180	325-250 BCE	Period 2	Emmer	5	4.6 \pm 0.1	-22.2 \pm 0.2
PVC	F 1121	325-150 BCE	Period 2	Emmer	5	4.6 \pm 0.7	-23.1 \pm 0.3
PVC	F 1121	325-150 BCE	Period 2	Free-threshing wheats	5	3.8 \pm 0.4	-22.8 \pm 0.3
YLH	F 1006	200-150 BCE	Period 2	Barley	5	4.4 \pm 0.3	-23.5 \pm 0.4
YLH	F 1006	200-150 BCE	Period 2	Free-threshing wheats	5	3.2 \pm 0.2	-22.6 \pm 0.2
YLH	F 1071	200-150 BCE	Period 2	Barley	5	5.8 \pm 0.7	-23.6 \pm 0.3
YLH	F 2057	275-250 BCE	Period 2	Barley	5	3.9 \pm 0.3	-22.3 \pm 0.2
YLH	F 2057	275-250 BCE	Period 2	Free-threshing wheats	5	3.2 \pm 0.1	-21.7 \pm 0.2
PVC	F 1251	150-80 BCE	Period 3	Emmer	5	6.8 \pm 0.5	-22.9 \pm 0.3
PVC	F 1251	150-80 BCE	Period 3	Free-threshing wheats	5	4.1 \pm 0.4	-23.0 \pm 0.2
PVC	F 4096	150-80 BCE	Period 3	Emmer	5	5.3 \pm 0.1	-22.0 \pm 0.1
PVC	F 4096	150-80 BCE	Period 3	Free-threshing wheats	5	5.0 \pm 0.4	-21.0 \pm 0.2

279 *Table 1. Stable nitrogen and carbon isotope values of cereal grains analysed for each grain group. n:*
 280 *number of analysed samples. Each sample includes 10 grains.*

281



282

283 *Figure 4. $\delta^{15}\text{N}$ of archaeological grains, grouped by grain group. Each point is one sample of 10 grains.*
 284 *Orange lines: thresholds for manuring rates after Fraser et al. 2011 and Bogaard et al. 2013 (below*
 285 *3‰, no manuring; 3-6‰, moderate or ancient manuring; above 6‰, high manuring rates).*

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	Group 1	Group 2	Difference $\delta^{15}\text{N}$ (‰) [90% CI]	DF	t	p
$\delta^{15}\text{N}$ depending on taxon and period pseudo- $R^2=0.91$ Taxon: $p=0.348$ – Period: $p=0.015$	Barley	Emmer	-0.2 [-1.5; 1.0]	13	-0.332	0.745
	Barley	Free-threshing wheats	-0.7 [-1.8; 0.4]	13	-1.199	0.252
	Period 1	Period 2	1.2 [0.2; 2.2]	13	2.088	0.057
	Period 1	Period 3	2.4 [1.2; 3.7]	13	3.403	0.005
Model bis: $\delta^{15}\text{N}$ depending on taxon and period (extract)	Emmer	Free-threshing wheats	-0.5 [-1.6; 0.6]	13	-0.834	0.419
	Period 2	Period 3	1.3 [0.0; 2.5]	13	1.831	0.090

290 Table 2. Results of the linear mixed-effects models ($\delta^{15}\text{N}$), with taxon and period as fixed effects and
 291 grain group as a random effect. p values <0.1 are shown in bold. Modelled difference: $\delta^{15}\text{N}_{\text{group 2}} -$
 292 $\delta^{15}\text{N}_{\text{group 1}}$

293

294 As the studied deposits are not necessarily synchronous within each period (each dating phase
 295 covers several decades), it is essential to analyse at a finer scale, *i.e.*, to compare the different cereal
 296 species from a same concentration, in order to compare agricultural treatments between cereals.
 297 Comparisons are made between barley and free-threshing wheats and between emmer and free-
 298 threshing wheats (Table 3). Sampling does not allow for direct comparisons between emmer and
 299 barley, because they were not found together.

300 In a given deposit, inter-cereal differences in $\delta^{15}\text{N}$ values can be high (1.3‰ and 2.7‰ for silos F1006
 301 and F1251 respectively). In the four silos where both barley and free-threshing wheats are present,
 302 barley always yielded higher $\delta^{15}\text{N}$ values on average, even though this difference is only relatively
 303 high in two cases (+0.7‰ in silo F2057, +1.3‰ in silo F1006), low in silo F1221 (+0.5‰) and null in
 304 F1001. Emmer always yielded similar or higher $\delta^{15}\text{N}$ values compared to free-threshing wheats
 305 (+2.7‰ in silo F1251, +0.7‰ in silo F1121, not significant difference in F4096).

306

Id Site	Silo	Group 1	Group 2	Difference $\delta^{15}\text{N}$ (‰) [90% CI]	p
YLH	F 1001, SU 19	Barley	Free-threshing wheats	0,0 [-0.8; 0.7]	0.675
YLH	F 1006	Barley	Free-threshing wheats	-1.3 [-1.6; -0.9]	0.012
PVC	F 1121	Emmer	Free-threshing wheats	-0.7 [-1.5; -0.3]	0.076
YLH	F 1221	Barley	Free-threshing wheats	-0, 5 [-1.5; 0.1]	0.222
PVC	F 1251	Emmer	Free-threshing wheats	-2.7 [-3.4; -2.2]	0.008
YLH	F 2057	Barley	Free-threshing wheats	-0.7 [-0.9; -0.4]	0.008
PVC	F 4096	Emmer	Free-threshing wheats	-0.4 [-0.8; 0.1]	0.151

307 Table 3. Results of the Wilcoxon rank-sum test, comparing the taxa by archaeobotanical deposit.
 308 p values <0.1 are shown in bold. Difference = $\delta^{15}\text{N}_{\text{group 2}} - \delta^{15}\text{N}_{\text{group 1}}$

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310

Id Site	Silo	Group 1 (SU 18)	Group 2 (SU 19)	Difference $\delta^{15}\text{N}$ (‰) [90% CI]	p
YLH	F 1001	Free-threshing wheats	Free-threshing wheats	-2.4 [-3.0; -1.7]	0.008
PVC	F 1001	Free-threshing wheats	Barley	-2.4 [-2.9; -1.8]	0.012

312 Table 4. Results of the Wilcoxon rank-sum test, comparing the grain groups from different
 313 stratigraphic units of the same silo F 1001. SU 18 is earlier than SU 19. p values <0.1 are shown in
 314 bold. Difference = $\delta^{15}\text{N}_{\text{group 2}} - \delta^{15}\text{N}_{\text{group 1}}$

315

316 4. Discussion

317 4.1. Manuring as a cause of increased $\delta^{15}\text{N}$ values

318 The great majority of cereal $\delta^{15}\text{N}$ values are above 3‰, reflecting ^{15}N -enrichment of cultivated soils
 319 by human activities in most cases. Nitrogen cycles are complex (Szpak, 2014) and several agricultural
 320 practices can influence the nitrogen isotopic composition of the environment (manuring, slash-and-
 321 burn cultivation, green manure). As shown by paleoenvironmental studies in the study area (Cousot,
 322 2010; Martin, 2010; Pradat, 2010) and palynological analyses at a regional scale (Blancquaert *et al.*,
 323 2012), deforestation intensified during the Iron Age. The area was densely inhabited for a long time,
 324 with long-term shifting habitats. Even if the whole area was not cultivated at the same time (*e.g.*,
 325 with fallow spaces), the land must have been cleared a long time ago and potential clearing or
 326 burning effects are unlikely. At the three farms, evidence for legume cultivation is scarce (less than
 327 3% of food plant remains), as observed on a very large corpus of sites in the Paris Basin (Zech-
 328 Matteredne *et al.*, 2014, 2020), so their impact on soil quality must have been minimal. Hence, one of
 329 the main causes of $\delta^{15}\text{N}$ evolution is, in this case, the spreading of animal and human excrement
 330 either in the form of manure collected from stalls or by the mobile penning of livestock on land.

331 Stables and dung-yards are rare on Iron Age sites. Very few of them are known in France (Bosche *et*
 332 *al.*, 2009, pp. 68–71; Gaudefroy, 2016, p. 107; Hinguant *et al.*, 1998, pp. 74–83; Mathiot, 2012) and
 333 none was positively identified at the sites studied here. This rarity can be explained by cultural as
 334 well as taphonomic factors (these features are identified in Roman farms). Indeed, it has been argued
 335 that livestock (Caprinae, pigs, and a few cattle; Bayle, 2011, 2010) were not stalled, but herded
 336 outdoors, with light shelters (Zimmermann, 1999). Penning livestock on cultivated plots during
 337 intercrop periods after daily grazing fertilises the land without having to store and transport manure.
 338 Ditch cleaning, farm waste, as well as human or pig excrement may have been another source of
 339 fertiliser, especially for fields closer to the farm, due to transport limitations.

340 During Period 1 (400/325 BCE), the $\delta^{15}\text{N}$ values of half the grain groups are below 3‰. Thereafter,
 341 $\delta^{15}\text{N}$ values increase continuously, with all measurements exceeding the 3‰-threshold and one of
 342 more than 6‰ at the Period 3 (emmer from silo F1251). This increase can be explained by
 343 continuous fertilisation over three centuries, gradually enriching the soil and plants in ^{15}N .

344 4.2. Relationship between agricultural practices and land use

345 The increase in $\delta^{15}\text{N}$ values from Period 1 (400/325 BCE) to Period 3 (150/80 BCE) suggests the
 346 repeated use of manure. This result is consistent with studies of other areas in northern France for
 347 Second Iron Age and Roman period (Aguilera *et al.*, 2018). This increase can be related to the
 348 evolution of habitats. Period 1 (400/325 BCE) corresponds to the installation of the major site of

349 Ymonville “Les Hyèbles”, adding a new large centre of production on the plateau, with agricultural
350 activities contributing to the ^{15}N -enrichment of cereals. During Period 2 (325/150 BCE), the
351 occupation of the area was dynamic, with the rise of Prasville “Vers Chesnay”. Sheep grazing
352 between crops and the use of pig and human manure may have increased soil and plant $\delta^{15}\text{N}$ values.
353 The third period was one of habitat restructuration (farm displacement and expansion). Another
354 source of manure may have been used, with cattle and horse rearing alongside sheep and pigs.

355 The three sites correspond to different social statuses. Ymonville “Les Hyèbles” was a major
356 aristocratic farm, Prasville “Vers Chesnay” an intermediate farm and Prasville “Les Grandes Canettes”
357 a smaller settlement. Despite these hierarchical differences, cereals show similar isotopic
358 composition, reflecting the sharing of agricultural practices and the same manure production
359 capacity between farmers from the same area. The variability of $\delta^{15}\text{N}$ values (over 5‰ amplitude)
360 suggests a wide range of soil fertility conditions, most probably linked to different manuring rates
361 and the history of plots.

362 4.3. Interspecific differences in nitrogen isotopic composition

363 Different cereal species growing under the same environmental conditions have comparable
364 nitrogen isotopic composition (Fraser *et al.*, 2011). Crops with similar $\delta^{15}\text{N}$ values (*e.g.* barley and
365 free-threshing wheats from the F 1001, SU 19) do not necessarily indicate that they were grown in
366 the same field, but rather that they were grown on soils with the same fertility. The majority of the
367 grain groups could have been fertilised, but differences are visible within the same archaeobotanical
368 deposit (Table 3). $\delta^{15}\text{N}$ values are greater for barley than for free-threshing wheats in two out of four
369 silos (F1006, F2057). The average difference is slight (around 1‰) but could nonetheless show that
370 barley was sometimes more carefully cultivated (more often manured), as observed during the
371 Hallstatt period in Germany (Styring *et al.*, 2017) and during the fifth century BCE in the city of
372 Lattara in southern France (Alagich *et al.*, 2018). The same observation applies to emmer, which is
373 more fertilised than free-threshing wheats (F1121, F1251). This contrasts with agronomic knowledge
374 of current varieties, where free-threshing wheats are more nutrient-demanding than barley and
375 emmer to ensure good yields. Farmers in Beauce chose to focus on fertilising certain crops, and not
376 necessarily the dominant crop (around 70% of cereal grains are free-threshing wheats during Period
377 1 in Ymonville “Les Hyèbles” and Period 2 in Prasville “Vers Chesnay”; Pradat, 2010, unpublished). By
378 contrast, Aguilera *et al.* (2018) observed preferential manuring of free-threshing wheats in the
379 neighbouring Ile-de-France region. This reflects regional differences already observed in agricultural
380 production at that time (Lepetz and Zech-Matterne, 2018).

381 4.4. Seizing agricultural practices in the very short term

382 Silo F1001 at Ymonville “Les Hyèbles” yielded grain groups from two successive stratigraphic units
383 (belonging to the same occupation phase). We can consider that these two infillings are closely
384 related in time, on account of the rapid obliteration of the holes by inhabitants, and the related
385 harvest dates separated by a few years at most. $\delta^{15}\text{N}$ values are very different between grain groups
386 (Table 4 and Figure 4), with cereals from the later stratigraphic unit yielding $\delta^{15}\text{N}$ values lowered by
387 2.4‰ compared to the earlier ones. Such a decrease in the soil nitrogen isotope composition is
388 unlikely over a few years, at most. Alternatively, the difference between the two successive harvests
389 could be explained by a wide variety of management strategies for different cultivated plots around
390 the farm. Some were manured while others were not. This assumption may explain diversity of $\delta^{15}\text{N}$
391 values through silos from a same period.

392 Methodologically, the case of silo F1001 (Ymonville “Les Hyèbles”) is interesting for sampling
393 strategies. Sampling archaeobotanical remains from several successive stratigraphic units from a
394 same structure records the short-term diversity of agricultural practices.

395 5. Conclusion

396 Results from the stable isotope analysis of charred cereal grains show that manuring was a solution
397 adopted by the Second Iron Age inhabitants of these three neighbouring farms to fertilise cultivated
398 soils. The main argument for this is high $\delta^{15}\text{N}$ values and their continuous increase over time,
399 reflecting the dynamism of agricultural activities in this area, causing ^{15}N -enrichment in the
400 environment as a result of manure application. The lack of stalling features raises the question of
401 livestock management and the possible mobile penning of livestock. These results suggest a mosaic
402 landscape around the farm, with cereal fields fertilised or not from one year to the next. Different
403 manuring rates may have been applied over time, space and cereal species, reflecting variability in
404 farmers’ choices. Manuring is not correlated with the dominant crop. The use of manure provided
405 the conditions for improving the agricultural economy.

406

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