1 **Isotope evidence for agricultural extensification reveals how the world's first**
2 **cities were fed**
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24 **Abstract**
25 This study sheds light on the agricultural economy that underpinned the emergence of
26 the first urban centres in northern Mesopotamia. Using $\delta^{13}C$ and $\delta^{15}N$ values of crop
27 remains from the sites of Tell Sabi Abyad, Tell Zeidan, Hamoukar, Tell Brak and Tell
28 Leilan (6500–2000 cal BC), we reveal that labour intensive practices such as
29 manuring/middening and water management formed an integral part of the
30 agricultural strategy from the seventh millennium BC. Increased agricultural
31 production to support growing urban populations was achieved by cultivation of
32 larger areas of land, entailing lower manure/midden inputs per unit area—
33 *extensification*. Our findings paint a nuanced picture of the role of agricultural

34 production in new forms of political centralisation. While the shift towards lower

35 input farming most plausibly developed gradually at a household level, the increased

36 importance of land-based wealth constituted a key potential source of political power,

37 providing the possibility for greater bureaucratic control and contributing to the wider

38 societal changes that accompanied urbanisation.

39

40 **Introduction**

41

42 **Strategies to increase crop production**

43 The emergence of the first urban centres represents a pivotal moment in human

44 history, and much research has focussed on changes in the political, social and

45 productive economy that accompanied and likely contributed to this change [1,2]. In this

46 study we consider the stable carbon isotope ($\delta^{13}C$) and nitrogen isotope ($\delta^{15}N$) values

47 of 276 charred cereal grain and 44 pulse seed samples (each comprising 4–25

48 individual grains/seeds) from the sites of Tell Sabi Abyad, Tell Zeidan, Hamoukar,

49 Tell Brak and Tell Leilan, located in the Khabur and Balikh drainage basins in

50 northern Mesopotamia and dating to between 6500 and 2000 BC (Figure 1; Table 1).

51 This allows us to investigate how the staple economy supported the new population

52 centres that emerged in the fourth and third millennia BC in northern Mesopotamia,

53 and thus to reconsider wider debates surrounding the agroecology of early urbanism,

54 its sustainability and the role of political centralisation in shaping some of the world's

55 earliest urbanised landscapes.

56

57 A generalised narrative of agricultural 'intensification' has long held sway in

58 discussion of early urbanisation around the world, in part due to emphasis on

59 irrigation-based societies [3]. Influential research based in southern Mesopotamia [4,5],

60 where irrigation is obligatory and associated with high area yields, has encouraged a

61 prevailing view that urban civilisation in the rainfed north was likewise supported by

62 investing higher labour inputs per unit area [2,6–8]. The productive potential of northern

63 Mesopotamia in recent times, however, has depended on very extensive cultivation,

64 augmented since World War One by tractors, pump irrigation and agrochemicals,

65 combined with effective systems of mobilisation and transport [9,10]. When did this

66 process of extensification begin? Was it initiated by the early cities of northern

67   Mesopotamia in the fourth and third millennia BC, or were these early urban centres

68   instead dependent on high-intensity land management like their southern

69   counterparts?

70

71   Although not always explicitly defined in discussion of agricultural practice, here we

72   refer to agricultural intensity in terms of labour and resource inputs per unit area of

73   land [11], placing the emphasis on the *intention* to increase outputs (crop yield) rather

74   than outputs *per se*. Agricultural *intensification* involves an increase in inputs,

75   resulting in increased crop yields per unit area of land. Practices that could have

76   involved high inputs of labour and resources include manuring or middening with

77   human, animal and/or household waste [8], controlling weeds through weeding or

78   turning over the soil and/or decreasing the frequency at which land was left fallow [12].

79   Management of the water available to crops, e.g. through strategic watering or

80   planting of less drought-tolerant crops in better watered settings/soils, may have been

81   another labour- and resource-intensive agricultural strategy in northern Mesopotamia,

82   given its relatively low (c. 200–500 mm/yr) and highly variable annual rainfall.

83   Increased agricultural production through agricultural *extensification*, by contrast, is

84   enabled by significant expansion of the land under cultivation, such that reduction of

85   inputs and yields per unit area are offset by a larger absolute scale of production [13].

86   Extensification can occur through implementation of labour-saving techniques such as

87   ploughing, specifically through use of specialized plough animals capable of

88   preparing a much larger area for sowing than can be achieved manually by a farming

89   family. Such radical expansion in arable scale requires an additional supply of labour

90   at harvest time, a system that implies a level of organisation of labour beyond the

91   immediate household.

92

93   Of course, increasing inputs per unit area or expanding the absolute scale of

94   cultivation are not mutually exclusive means of increasing production, and a mixture

95   of the two could be employed to meet the needs of a growing and aggregating

96   population. Indeed, scatters of abraded sherds (proposed to be derived from household

97   waste that was spread on fields to improve their fertility) and 'hollow ways'

98   (extensive tracks resulting from confining animal movement to areas between

99   cultivated fields) have been given as evidence for both intensification of manuring

100   and expansion of cultivated land in the third millennium BC [14,15], respectively. These

101   sherd scatters and 'hollow way' features can be difficult to date, however [16], and it is

102   possible that third millennium practices have obscured earlier evidence of manuring.

103   There is also no way of inferring from this off-site evidence whether cereals, pulses

104   and oil-seed crops were treated differently and thus how their management mapped

105   onto these landscapes.

106

107   **Directly determining agricultural intensity using crop isotope values**

108   Crop isotope values offer an opportunity to improve our understanding of how

109   agricultural strategies changed under urbanisation, delivering a complementary

110   approach to off-site methods that provides *direct* evidence for the growing conditions

111   of specific crops, better temporal resolution of changing farming practice and more

112   nuanced insight into the relative importance of intensification and extensification

113   among sites and contexts. Crop δ^{15}N values largely reflect the δ^{15}N value of the soil in

114   which they are grown, which in turn is strongly influenced by land use history [17]. In

115   particular, application of animal manure has been found to increase the δ^{15}N values of

116   soil and cereals by as much as 10‰, relating to the intensity—amount and

117   frequency—of manuring [18,19], as well as to the type of organic matter—compost,

118   animal manure, household waste—applied [20]. From now on, we use the term

119   manuring/middening to encapsulate the various means by which organic matter could

120   have been added to the soil. Intensive manuring/middening requires a high input of

121   labour—being heavy to transport and spread —and in modern farming studies usually

122   goes hand-in-hand with other labour-intensive cultivation practices such as weeding

123   and hoeing, since it enhances the tractability (ease of working) of soil [21]. Crop δ^{15}N

124   values can therefore act as a proxy for the general intensity of agricultural practice, or

125   labour inputs per unit area. Crop δ^{13}C values reflect the movement of carbon dioxide

126   through the stomata, which in dry climates is most strongly influenced by the water

127   status of a crop during its growth period [22]. Since rainfall was relatively low at some

128   of the sites and during some of the time periods in our study—and thus marginal for

129   rainfed farming—it is possible that the water status of crops was manipulated in some

130   way, whether through direct watering or by strategic planting of relatively demanding

131   crops in areas with greater water availability such as the bottoms or slopes of wadis.

132   Crop δ^{13}C values can therefore help to elucidate how cultivation was configured in

133   the landscape and identify strategic (and potentially high input) crop management in

134   relation to water resources.

135

136   In this study we aim to provide a better understanding of how agricultural intensity

137   changed during two phases of urbanisation in northern Mesopotamia: the Late

138   Chalcolithic period (4400–3000 cal BC) and the Early Bronze Age (2600–2000 cal

139   BC). Lawrence and Wilkinson [23] have identified three distinct pathways to urbanism,

140   characterised by different site types: 'hub sites', which grew slowly in areas of

141   already dense and gradually increasing population (e.g. Tell Brak and Late

142   Chalcolithic Hamoukar); 'endogenous upstarts', which developed rapidly through the

143   movement of local populations into the urban centre (e.g. Tell Leilan); and

144   'exogenous upstarts', which also developed rapidly but in areas with little pre-existing

145   settlement. Within this framework, we can determine whether these contrasting urban

146   trajectories, with likely different underlying social contexts, entailed different forms

147   of agricultural practice at Tell Brak, Hamoukar and Tell Leilan. The political and

148   productive economies of these sizeable population centres are compared to those of

149   the Late Neolithic settlement of Tell Sabi Abyad (c. 6500–5200 cal BC) and the

150   Ubaid–Late Chalcolithic 2 town of Tell Zeidan (c. 5300–3850 cal BC). These data

151   will constrain current models of agricultural intensity and give an unparalleled insight

152   into changing agricultural practice through time, as settlements expanded and

153   contracted, and city-states became established. Moreover, by considering *direct*

154   evidence of crop growing conditions and farming practice, we hope to provide a

155   counterpoint to top-down 'elite' views of agricultural production and move towards a

156   more 'bottom-up farmer-centric perspective' of agricultural change [24].

157

158   **Results**

159

160   **Determining manuring intensity at archaeological sites**

161   Aridity can increase plant δ^{15}N values [e.g. 25] and it is therefore necessary to take this

162   into account when inferring manuring intensity from cereal grain δ^{15}N values. Styring

163   et al. [19] used the relationship between modern plant δ^{15}N values and rainfall in the

164   eastern Mediterranean [26] to adjust expected manuring rates based on δ^{15}N values of

165   cereal grains grown on controlled farming plots in temperate Europe [18,27]. While this

166 allows more accurate (and more conservative) estimates of manuring intensity from

167 cereal grain $\delta^{15}N$ values in semi-arid regions, here we use the cereal grain isotope data

168 from our studies of modern farming regimes across a wider range of rainfall zones

169 [18,19,28] to refine this method. Figure 2 shows cereal grain $\delta^{15}N$ values from present-day

170 farming regimes, colour-coded by their known manuring level, plotted against the

171 natural log of annual rainfall derived from interpolation of average monthly climate

172 data for 1960–1990, available from the WorldClim database [29]. High manuring

173 represents annual manuring of crops at rates equivalent to 30+ tonnes manure/ha;

174 medium manuring represents either annual or biennial manuring of crops at lower

175 levels (less than 20 tonnes/ha); and low manuring represents no manuring within the

176 last 3+ years. The lines represent a fitted linear model relating cereal grain $\delta^{15}N$

177 values to mean annual rainfall for each manuring level.

178

179 In this study we use a method called Bayesian multiple imputation [30] to assign

180 manuring levels to the archaeological samples and simultaneously test for a

181 relationship between these assigned manuring levels and site-related parameters such

182 as size and date (see Supplementary Information for more details). In the first

183 "imputation" stage of multiple imputation, the probability of each cereal grain sample

184 having each manuring level value is derived. Cereal grain $\delta^{15}N$ values, known

185 manuring levels and rainfall data from our studies of modern farming regimes inform

186 the regression parameters, and these combine with the $\delta^{15}N$ values and past rainfall

187 ranges of the archaeological material to assign the missing manuring level value (raw

188 archaeological crop $\delta^{15}N$ values in Figure 3 and Supplementary Table 1). We also

189 allow for uncertainty in past rainfall level values.

190

191 In the second "analysis" stage of multiple imputation we sample multiple assigned

192 manuring level data sets from the manuring level probability distribution we specified

193 at the first stage. We analyse each of these data sets and combine the analyses. In this

194 way our analysis allows for uncertainty in the assigned manuring levels. At this stage

195 of our analysis, manuring level is an outcome that is potentially explained by site size

196 and other site-specific covariates, such as date. We therefore regress our assigned

197 manuring level data on site size and test for a negative (i.e. one sided) effect. Site size

198 is based on field surveys of concentrated surface sherd scatters (as opposed to the

199 continuous and more sparse scatters of small, abraded sherds that have been

200 interpreted as manuring) and targeted excavation (see Table 1 for references). We use

201 a mixed-effects proportional-odds regression model for the three-level ordinal

202 manuring level outcome (low, medium, high). We include a random effect due to site

203 in order to model unmeasured site-specific variables that might influence the outcome

204 and to allow for uncertainty in sample date. Given a particular set of assigned

205 manuring levels we carry out Bayesian inference using flat priors, so that all remotely

206 possible parameter values are equally probable *a priori*. The posterior probability

207 distribution for the site size regression parameter is the average of the posterior

208 distributions taken over for each of the assigned manuring level data sets. The final

209 estimated posterior odds (equivalently here, the Bayes Factor) are 5.5 to 1 in favour of

210 a negative effect of site size on the manuring level of cereal grains (Figure 4). This

211 estimate incorporates all of the important sources of uncertainty and gives substantial

212 support for an effect of site size on cereal grain manuring levels.

213

214 The downside of Bayesian multiple imputation is its relative complexity. In order to

215 make the essential logic of the analysis more accessible, we repeated the analysis

216 using a very simple single imputation approach, and tests based on the maximum

217 likelihood estimator (see Supplementary Information for more details). Based on the

218 fitted linear model relating modern cereal grain δ^{15}N values to mean annual rainfall

219 for each manuring level (Figure 2), each archaeological sample of cereal grains is

220 assigned the manuring level that *predicts* a δ^{15}N value as close as possible to the

221 *observed* δ^{15}N value for that sample. We then regress this assigned manuring level

222 against site size using the mixed-effects proportional-odds regression model described

223 above and test for a negative effect due to site size (using a Wald test). Again, we find

224 clear evidence for an effect (p=0.0034), but note that this figure does not allow for

225 uncertainty in the imputed manuring levels as the multiple imputation approach does.

226 All our analyses are explained in more detail in the Supplementary Information.

227

228 **Spatial variation in agricultural strategy**

229 The variability in the δ^{15}N values of archaeological cereal grain samples demonstrates

230 that cereals were grown under a range of manuring conditions at each of the

231 archaeological sites (Figure 3). It seems that we can exclude floodplain cultivation as

232   a potential cause of high $\delta^{15}N$ values (denitrification during seasonal flooding can

233   result in enrichment of soil ^{15}N [31]) because $\delta^{15}N$ values of modern barley grains

234   grown without manure in dry wadi beds that were temporarily flooded following

235   heavy winter rains in 2014 in the south of Morocco are included in both manuring

236   level imputation models. However, isotope analysis of more cereals growing in

237   seasonally flooded settings would be beneficial to test this observation. The large

238   number of cereal grain samples with high $\delta^{15}N$ values (and thus with a low probability

239   of having a medium or lower manuring level; Figure 4) at Tell Sabi Abyad

240   demonstrates that manuring/middening formed an integral part of the agricultural

241   strategy from as early as the seventh millennium cal BC in northern Mesopotamia,

242   rather than developing later as a reaction to the need to feed a growing population [e.g.

243   12].

244

245   Since manure is a heavy and bulky resource to transport, manuring intensity is

246   generally governed by frictions of distance and is thus likely to be highest in plots

247   immediately surrounding settlement areas where animal dung from stabled livestock

248   and/or midden material accumulates [8]. Spatially, then, it is plausible that variable

249   manuring levels within an archaeological site reflect a spectrum of manuring intensity

250   radiating out from the settlement—from intensively managed 'infield' areas to more

251   extensively managed fields further away from the urban core. This model mirrors the

252   'halos' of abraded pot sherd scatters surrounding many third millennium BC urban

253   centres and the radiating track ways ('hollow ways') that extend beyond these scatters

254   and are believed to delineate the extent of arable cultivation [8].

255

256   There is also evidence that individual households had access to cereals grown under a

257   range of conditions, presumably harvested from plots at varying distances from the

258   site. Barley and glume wheat (einkorn and emmer) grain samples (n=8) representing

259   material stored in separate pots in a single household at LC3–4 Tell Brak, cleaned of

260   weed seeds and sieved for human consumption [32], have $\Delta^{13}C$ values (converted from

261   determined $\delta^{13}C$ values, see Methods section) and $\delta^{15}N$ values ranging from 15.1–

262   18.4‰ and 1.3–8.6‰, respectively. The large range in crop isotope values

263   demonstrates that household cereal stores derived from plots encompassing a wide

264   spectrum of agricultural intensity. This is consistent with the household having access

265 to land at a range of distances from the urban centre; higher manure inputs could be

266 maintained on plots closer to the settlement and better water retention was likely on

267 soils closer to the Wadi Jaghjagh and Wadi Radd, c. 3 km from the site [33]. There is

268 also the possibility that some of the crops had come from surrounding villages as a

269 form of tribute [34] or that crops were farmed on communal land, but while it cannot

270 necessarily be assumed that this household farmed/owned the disparate plots of land

271 from which their crops came, its access to such variable production points to a risk-

272 buffering strategy in the household's own interest [cf. 35].

273

274 **Changing agricultural practice**

275 Both the single and multiple imputation approaches show that the probability that

276 cereals received low levels of manure tends to increase as site size increases (Figure

277 4). Although attempting to relate settlement size to population is fraught with

278 uncertainty [36], given the large range in settlement size considered in this study—from

279 the 1 ha village of Tell Sabi Abyad to the 130 ha sprawl of early fourth millennium

280 BC Tell Brak—we feel it is valid to treat site size as at least a *general* index of

281 population. The results of the imputation models predict that as settlements in

282 northern Mesopotamia expanded and agricultural production increased, cereals were

283 grown with lower manure inputs per unit area, suggesting that to sustain greater

284 agricultural production, the area of land under cultivation must have increased

285 through a process of extensification. Whilst overall effort expended in manuring plots

286 may well have increased at larger settlements, the crop isotope results demonstrate

287 that the *bulk* of the increase in cereal production came from expansion of less

288 intensively manured plots, plausibly those lying beyond the immediate environs of the

289 urban centre.

290

291 Our results support the findings of Araus et al. [37], who observed a general trend of

292 decreasing cereal grain $\delta^{15}N$ values through time at various sites in the Near East.

293 Araus et al. [37] interpreted this general decrease in cereal $\delta^{15}N$ values through time as a

294 decrease in soil fertility that could have been caused by myriad potential factors,

295 including agricultural overexploitation, cultivation of marginal lands and reduced

296 manure application. Our model strongly indicates that increasing site size, resulting in

297 a deliberate change in agricultural practice that involved decreased manuring inputs,

298 was a more important factor in decreasing crop $\delta^{15}N$ values than soil degradation

299 resulting from years of poor agricultural management. This is exemplified by the

300 higher proportion of low-level manured cereal grain samples at 130 ha Tell Brak (c.

301 3800–3600 cal BC) compared to the contemporary 15 ha site of Hamoukar (Figure

302 4a).

303

304 Until now, scatters of abraded sherds dated to the third millennium BC have been

305 interpreted as the earliest evidence for manuring at Tell Brak, thus reflecting an

306 intensification of agricultural inputs during the Early Bronze Age [7,8]. Our new results

307 reveal that the appearance of these sherd scatters does not correlate with an increase in

308 manuring level, at least of *cereal*s. Complementary weed ecological data from Tell

309 Brak show that fertility levels in cereal fields were also relatively low at this time,

310 which is consistent with fields receiving low organic matter/manure inputs [38]. Thus,

311 while sherd scatters are considered to be a visible and persistent sign of the spreading

312 of organic household waste, perhaps this practice primarily benefited garden crops [8, 14]

313 and/or was necessitated due to a decrease in the availability of animal manure,

314 perhaps due to competing demands for its use as fuel [39]. A shift to a highly specialised

315 pastoral economy focussed on sheep and goat driven by the commodification of

316 textile production in the third millennium BC [40], together with the expansion of land

317 under arable production, would have extended herding into more marginal areas,

318 thereby reducing the opportunity for manure collection. The relatively high proportion

319 of cereal grain samples receiving low levels of manure at this time demonstrates that

320 any manuring of fields by animals allowed to graze on stubble or fallow land was not

321 comparable with the increase in cereal grain $\delta^{15}N$ values that result from deliberate

322 spreading of stall manure.

323

324 **Crop management in relation to water resources**

325 The archaeological cereal grain and pulse seed $\delta^{13}C$ values, which have been

326 converted into $\Delta^{13}C$ values to allow comparison with modern crop studies (see

327 Methods section), can reveal crop management strategies and thus provide insight into

328 how arable land was configured to exploit the hydrology of the landscape. Figure 5

329 shows the $\Delta^{13}C$ values of hulled barley, wheat (free-threshing and glume wheats) and

330 pulses (lentil, pea and grass pea) through time. There are no significant changes in

331   crop Δ^{13}C values across the time period studied, something that would be expected if

332   the water status of crops was governed solely by the variable rainfall (see

333   palaeoclimate records from e.g. Lake Van and Soreq Cave [41,42]).

334

335   The lack of significant variation in crop Δ^{13}C values with time suggests that there was

336   some degree of crop management in relation to water resources at all of the sites. This

337   observation need not necessarily equate to irrigation or deliberate watering, but

338   minimally implies that crops were strategically sown in areas with better water

339   availability, perhaps close to wadis or in soils/areas that retained water, to buffer them

340   from the effects of low rainfall. A study of barley grain Δ^{13}C values by Riehl et al. [43]

341   from archaeological sites across the Fertile Crescent observed lower Δ^{13}C values

342   (indicative of poorer water status) during aridification episodes *only* in the most

343   marginal settings for agriculture. Thus, our results and those reported by Riehl et al. [43]

344   reflect the difficulty of using crop δ^{13}C values as evidence of climate change *per se*,

345   but instead highlight their potential to measure agronomic adaptation to

346   (independently verified) climate change.

347

348   There is also no significant difference in the Δ^{13}C values of barley, wheat and pulses

349   [cf. 44]. Modern studies have shown, however, that if barley is grown in the same

350   watering conditions as wheat and pulses, it will tend to have a higher Δ^{13}C value;

351   offsets range from 1‰ in two-row barley to 2‰ in six-row barley [e.g. 45,46]. There are

352   indications that the Δ^{13}C values of ancient barley and wheat were also offset, though

353   the magnitude of this offset may have been smaller: six-row barley grain samples

354   (n=59) recovered from the archaeological site of Hornstaad-Hörnle IA, Germany

355   (3909 cal BC) have Δ^{13}C values that are 1.1‰ higher than those of wheat grain

356   samples (naked wheat and einkorn; n=120) grown in the same year [47]. Since these

357   cereals were unlikely to have received additional water inputs, this demonstrates that

358   a c. 1‰ difference in the Δ^{13}C values of barley and wheat grown in the same watering

359   conditions is observed in these ancient crops. Data from Neolithic Kouphovouno,

360   Greece are also consistent with an offset between two-row hulled barley and wheat,

361   though crop remains here do not derive from a single year's harvest, and were

362   conceivably affected by water management in a Mediterranean zone [48]. When crop

363   Δ^{13}C values are plotted against watering bands adjusted for the physiological

364 differences between barley (mostly two-row) and other crops (Figure 5), the majority

365 of the barley grain samples fall into the poor and moderately watered bands defined

366 by Wallace et al. [46], suggesting that yields were limited by water availability. In

367 contrast, the majority of wheat and pulse samples fall into the well watered band

368 (yields are not limited by water availability). The better water status of wheats and

369 pulses compared to barley further supports an hypothesis of strategic agricultural

370 practice because, at least today, barley generally tolerates drier conditions better than

371 wheat, peas and lentils [49]. This strategy would therefore have maximised overall crop

372 yields in a region where water availability likely presented a key limitation to the

373 optimal growth of crops.

374

375 **The role of cereals in the economy**

376 Plotting carbon and nitrogen isotope values of human and faunal bone collagen

377 alongside crop isotope values can reveal the importance of crops in the diet of both

378 humans and animals. Figure 6 shows the isotope values of crops, fauna and humans

379 from the Late Chalcolithic and Early Bronze Age at Tell Brak and for the Early

380 Bronze Age at Tell Leilan (faunal and human bone collagen $\delta^{13}C$ and $\delta^{15}N$ values are

381 in Supplementary Table 2). Shaded ellipses represent the expected distributions (mean

382 ± 2 standard deviations) of $\delta^{13}C$ and $\delta^{15}N$ values of individuals consuming various

383 dietary combinations of cereal grains, pulses and animal products (milk and/or meat).

384 The determined human isotope values (with their mean ± 2 standard deviations

385 distribution outlined in black) clearly overlap more closely with the ellipses

386 corresponding to lower animal protein consumption in all periods, suggesting that

387 cereal grains were likely an important part of the human diet (cf. grain ration records

388 [50]).

389

390 During LC3–4, in particular, there is a shift towards higher faunal $\delta^{13}C$ values,

391 indicating greater C_4 plant consumption (e.g. *Cyperus*, *Eragrostis*), which is

392 consistent with grazing on more marginal steppe areas that received lower rainfall.

393 While consumption of C_3 plants growing in areas of lower water availability would

394 also result in higher faunal $\delta^{13}C$ values, the particularly high $\delta^{13}C$ values of some of

395 the fauna (> −18‰), can only be due to consumption of C_4 plants with $\delta^{13}C$ values of

396 c. 14‰ [51]. Tell Brak was 130 ha in extent at this time, and the expansion in cultivation

397   indicated independently by the crop isotope values would plausibly have

398   complemented this movement of animals away from the settlement. In the Early

399   Bronze Age at Tell Leilan, the faunal isotope values overlap entirely with the ellipse

400   for 100% cereal grain consumption, indicating that a significant portion of the

401   herbivore and pig diet could also have comprised cereal grains. The possibility of

402   cereal grains being grown as fodder for domestic herbivores has been suggested

403   previously on the basis of archaeobotanical findings of large quantities of un-cleaned

404   barley grains at Tell Brak [52] and Tell Leilan [53], and textual references to allocations of

405   cereals as animal fodder [50].

406

407   **Discussion**

408

409   The cereal grain isotope values from archaeological sites in the Khabur and Balikh

410   drainage basins provide a spatial and temporal perspective on changing agricultural

411   practice prior to and during two phases of urbanisation. The relatively small

412   settlements of Tell Sabi Abyad and Tell Zeidan (1 and 12 ha, respectively) yielded

413   cereal grains with relatively high δ^{15}N values that are consistent with high levels of

414   manuring/middening being practiced from as early as the seventh millennium BC,

415   thousands of years earlier than the appearance of sherd scatters that have previously

416   been the primary evidence for manuring [14]. This evidence for early manuring is

417   contrary to evolutionary models of agricultural development that suggest that highly

418   labour intensive practices such as manuring were only employed when population

419   pressure induced such changes [12]. Moreover, we find that strategic crop management

420   in relation to water resources played a key role in cereal and pulse cultivation at even

421   the early sites [44,54], likely as a deliberate means of ensuring adequate production in

422   such a water-limited region. The centrality of cereals in both human and animal diets,

423   as seen in bone collagen isotope values, explains this considerable investment.

424

425   Cereal grain nitrogen isotope values reveal that increased agricultural production to

426   support growing urban populations in northern Mesopotamia was achieved by

427   cultivation of larger areas of land, using lower manure/midden inputs per unit area—

428   *extensification* [9]. This evidence for expansion of arable land is in agreement with off-

429   site survey evidence for extensive arable catchment areas around urban centres

430 (mainly in the third millennium cal BC), indicated by radiating 'hollow ways' [8] and

431 regional surveys of site distributions [10,55]. It also aligns with the economies of scale

432 gained from aggregations of population [56], since there would have been a supply of

433 labour at crucial bottlenecks in the agricultural year (such as harvest time) that could

434 be mobilised from amongst other cadres of society (cf. Sumerian city-states [57]).

435 Extensification as a means of increasing arable production is in line with the model of

436 extensive agriculture proposed by Weiss [9,10] for northern Mesopotamia and Halstead

437 [13] for the provisioning of the urban palatial economies of Late Bronze Age southern

438 Greece, and with evidence for highly intensive management from the initial

439 establishment of farming in Europe [27] and the Near East [19,58].

440

441 The relationship between agricultural intensity and settlement size transcends third to

442 fourth millennium BC differences in social complexity and urban form [23]. Thus, the

443 shift towards lower input farming at larger urban centres most plausibly developed

444 gradually at a household level; as households sought to increase production, plots

445 receiving low labour inputs expanded relative to the more intensively managed plots.

446 Moreover, while our data are consistent with an overall strategy of extensification,

447 this broader framework subsumes a range of behavioural variation that is testimony to

448 a bottom-up as opposed to top-down driver of agricultural change. Individual

449 households seem to have practiced a nuanced and flexible strategy in which: a) the

450 crops planted, b) where they were planted, and c) labour and material inputs of water

451 and/or manure were all fine-tuned to the specific characteristics of the crop, land

452 and/or soil quality, and the highly variable rainfall circumstances of any given year.

453 This diversity in agricultural practice makes sense as a household risk-buffering

454 strategy but not as an elite-controlled share-cropping regime [35].

455

456 Nonetheless, this extensive agriculture directly ties production to the amount of land

457 under cultivation—rather than to inputs and therefore to yields per unit area—and

458 heightens the importance of land-based wealth that can be transferred from generation

459 to generation [59]. Thus, extensification could fuel inherited wealth inequality as a

460 potential source of political power. Linking agricultural outputs to land rather than

461 labour inputs also provides a much more tangible measure upon which to base levels

462 of taxation/tribute [60], permitting greater bureaucratic control over surplus, which

463 could have benefited those in political power. Ultimately, this study reveals that the

464 expansive agricultural economy was integral to the development of these first

465 northern Mesopotamian cities, driving—as well as being driven by—the wider

466 societal changes that accompanied this urban trajectory.

467

468

469 **Methods**

470

471 **Modern cereal grains.** Carbon and nitrogen isotope analysis was carried out on 273

472 cereal grain samples (each representing a homogenised batch of 50 cereal grains of

473 the same taxon) from 14 farming sites/regions. Details of the site locations, mean

474 annual rainfall, taxon and manuring regimes for each of the crop samples are in Table

475 2. The grains in each sample were homogenised prior to isotope analysis using a Spex

476 2760 FreezerMill.

477

478 **Archaeological cereal grains.** Carbon and nitrogen isotope analysis was carried out

479 on 276 cereal grain and 44 pulse seed samples (each representing a homogenised

480 batch of 4–25 grains/seeds of the same taxon) from five archaeological sites. Twenty-

481 seven of the samples from Tell Brak are the same as those whose $\Delta^{13}C$ values are

482 reported in Wallace et al. [44]; these are identified in Table S1. Cereal grains were

483 recovered in a carbonised state from a range of contexts including storage rooms,

484 domestic fires, cooking ovens and floors. The chronology of crop samples was based

485 on stratigraphic dating and radiocarbon ages. Details of the site locations, present-day

486 mean annual rainfall, estimated past rainfall ranges and settlement size can be found

487 in Table 1 and isotopic data for each of the crop samples are listed in Table S1.

488

489 **Human and faunal bone collagen.** Carbon and nitrogen isotope analyses were

490 carried out on bone and dentine collagen isolates of 60 humans and 31 herbivores

491 (cattle, gazelle, goat and sheep) from LC2, LC3–4 and EBA Tell Brak and 7 humans,

492 13 herbivores (cattle, gazelle, goat and sheep) and 8 pigs from EBA Tell Leilan. The

493 occupation periods were selected based on those that had isotope data for crops, fauna

494 and humans. Details of the archaeological contexts in which bones were found,

495 chronology and isotopic data for each of the bone collagen isolates are listed in

496 Supplementary Table 2. Only collagen values with C/N ratios between 2.9 and 3.6

497 were studied, following quality criteria described by DeNiro [61], and samples with a

498 collagen yield < 1% were visually inspected to ensure that they looked like collagen.

499

500 **Preparation of carbonised crop remains for isotope analysis.** Cereal grains and

501 pulse seeds were examined at ×7–45 magnification for visible surface contaminants,

502 such as adhering sediment or plant roots; these were removed by gentle scraping.

503 Around 10% of the total number of samples from each site were scraped clean,

504 crushed and analysed using Fourier transform infrared spectroscopy with attenuated

505 total reflectance (FTIR-ATR) to look for the presence of carbonate, nitrate and/or

506 humic contamination [62]. Peaks characteristic of carbonate contamination (870 and 720

507 cm^{-1}) were observed in three of the FTIR spectra of samples from Tell Brak but in

508 none of the FTIR spectra from other sites (Supplementary Figure 1). It was therefore

509 decided to acid pre-treat all of the crop samples from Tell Brak to dissolve any

510 carbonate [63]. This procedure consists of treatment with 10 ml of 0.5 M hydrochloric

511 acid at 70°C for thirty to sixty minutes, then rinsing in distilled water three times

512 before freeze-drying. This acid pre-treatment does not affect the isotope values of

513 charred grains in the absence of contamination [62]. The samples (both acid pre-treated

514 and untreated) were crushed using an agate mortar and pestle.

515

516 **Preparation of bones and dentine for isotope analysis.** Between 0.5 and 1 g of

517 bone/dentine was cleaned of any visible dirt or carbonate crusts using an aluminium

518 oxide air abrasive. Collagen was isolated using a modified 'gelatinization method'

519 based on the methods of Longin [64] and ultrafiltered prior to isotope analysis.

520

521 **Stable carbon and nitrogen isotope analysis.** All samples (modern and

522 archaeological, crop and bone collagen) were weighed into tin capsules for stable

523 isotope analysis. The $\delta^{13}C$ and $\delta^{15}N$ values of cereal grains and bone collagen were

524 determined on a SerCon EA-GSL mass spectrometer. The $\delta^{13}C$ and $\delta^{15}N$ values of

525 crops were determined in separate runs due to the low %N in the samples. An internal

526 alanine standard was used to calculate raw isotope ratios. For $\delta^{13}C$ determinations of

527 crops, two-point normalization to the VPDB scale was carried out using four

528 replicates each of IAEA-C6 and IAEA-C7, while for $\delta^{15}N$ determinations the

529 standards were caffeine and IAEA-N2. For $\delta^{13}C$ and $\delta^{15}N$ determinations of bone

530 collagen, two-point normalization was carried out using four replicates each of

531 caffeine and seal bone collagen. Reported measurement uncertainties are the

532 calculated combined uncertainty of the raw measurement and reference standards,

533 after Kragten [65]. The average measurement uncertainties for $\delta^{13}C$ and $\delta^{15}N$ values of

534 crops were 0.09‰ and 0.20‰, respectively. The average measurement uncertainties

535 for $\delta^{13}C$ and $\delta^{15}N$ values of bone collagen were 0.09‰ and 0.18‰, respectively.

536 These calculations were performed using the statistical programming language R

537 (3.0.2). The $\delta^{13}C$ and $\delta^{15}N$ values of carbonised crop remains were corrected for the

538 effect of charring by subtracting 0.11‰ and 0.31‰, respectively, from the determined

539 $\delta^{13}C$ and $\delta^{15}N$ values, which are the average offsets between uncarbonised crop seeds

540 and those heated for 4, 8 or 24 hours at 215, 230, 245 or 260°C [66].

541

542 **Conversion of $\delta^{13}C$ values to $\Delta^{13}C$ values.** The $\Delta^{13}C$ values of modern cereal grains

543 were calculated from the determined $\delta^{13}C$ values ($\delta^{13}C_{plant}$) and an average $\delta^{13}C$ value

544 of atmospheric CO_2 ($\delta^{13}C_{air}$) determined from air sampled at weekly intervals during

545 the months that the crops were growing [67], using the equation below. The $\Delta^{13}C$ values

546 of archaeological cereal grains were calculated from the determined $\delta^{13}C$ values

547 ($\delta^{13}C_{plant}$) and a $\delta^{13}C_{air}$ value approximated by the AIRCO2_LOESS system [45]. The

548 equation was defined by Farquhar et al. [22]:

549
550
$$\Delta^{13}C = \frac{\delta^{13}C_{air} - \delta^{13}C_{plant}}{1 + \delta^{13}C_{plant}/1000}$$

551

552 **Estimating past annual rainfall at archaeological sites.** We have used the

553 difference between past and present-day annual rainfall at Soreq Cave (location in

554 Figure 1 [68]), estimated from speleothem $\delta^{18}O$ values and the present-day calibration

555 relationship between speleothem $\delta^{18}O$ values and rainfall, to adjust present-day

556 annual rainfall at each of the archaeological sites and thus estimate past rainfall at

557 200-year intervals (a 1‰ decrease in the $\delta^{18}O$ value of precipitation is equivalent to

558 an increase in annual rainfall of c. 200 mm [68]). The uncertainty associated with these

559 estimates is accounted for in the multiple imputation model. Recent work has found

560 that $\delta^{18}O$ values of rainfall can be affected by the type of precipitation (convective or

561 stratiform) as well as by the amount, and so these estimates of past annual rainfall

562 based on the speleothem $\delta^{18}O$ values may well be modified in the future [69]. Although

563   estimating past rainfall from a proxy record located c. 700 km away from the study

564   sites is problematic, the general trend in climate is similar to that for other lower-

565   resolution proxy records closer to the region. The $\delta^{18}O$ values of sediments from Lake

566   Mirabad in southwest Iran, Lake Zeribar in western Iran, and Lake Van in southeast

567   Turkey (locations in Figure 1) also show generally wetter conditions than today

568   between c. 7000 and 4000 BC followed by a trend towards greater aridity in the third

569   millennium BC [42,70,71]. Dry phases indicated by higher $\delta^{18}O$ values in c. 4500 BC,

570   3300–3000 BC and 2500–1950 BC are also observed in multiple records [72].

571

572   **Visualising potential dietary scenarios.** Figure 6 shows the expected distributions

573   (mean ± 2 standard deviations) of $\delta^{13}C$ and $\delta^{15}N$ values of individuals consuming

574   various dietary combinations of cereal grains, pulses and animal products (milk and/or

575   meat). The expected $\delta^{13}C$ and $\delta^{15}N$ value distribution of humans consuming 100%

576   cereal grains are estimated by adding consumer-diet offsets of 4.8‰ [73] and 4‰ [74],

577   respectively, to the determined cereal grain $\delta^{13}C$ and $\delta^{15}N$ values. The expected $\delta^{13}C$

578   and $\delta^{15}N$ value distribution of humans consuming 100% pulses are estimated by

579   adding consumer-diet offsets of 4.8‰ [73] and 4‰ [74], respectively, to the determined

580   pulse $\delta^{13}C$ and $\delta^{15}N$ values. Since the consumer-diet $\delta^{13}C$ value offset is smaller

581   between carnivores and herbivores than between herbivores and plants [72], the

582   expected $\delta^{13}C$ and $\delta^{15}N$ value distribution of humans consuming 100% animal protein

583   are estimated by adding consumer-diet offsets of 0.8‰ [73] and 4‰ [74], respectively, to

584   the determined faunal bone collagen $\delta^{13}C$ and $\delta^{15}N$ values. The expected $\delta^{13}C$ and

585    $\delta^{15}N$ value distributions of humans consuming mixtures of these diets (20, 50 and

586   80% animal protein, with the remaining proportion of the diet comprising a 50:50 mix

587   of cereal grains and pulses) are estimated by adding the appropriate consumer-diet

588   offsets to the $\delta^{13}C$ and $\delta^{15}N$ values of the dietary components, and multiplying each

589   by their proportion in the diet.

590

591   **Data availability.** Raw $\delta^{13}C$ and $\delta^{15}N$ values of the archaeological crop samples are

592   given in Supplementary Table 1. Raw $\delta^{13}C$ and $\delta^{15}N$ values of the modern crop

593   samples used to infer the manuring levels of the archaeological crop samples are

594   given in Supplementary Information (SI3). Full details of the statistical analysis

595   (including R files) are available in Supplementary Information (SI1–19). The raw

596     $\delta^{13}C$ and $\delta^{15}N$ values of the archaeological animal and human bone collagen are given

597   in Supplementary Table 2.

598

599

600

601

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802   **Corresponding author.** Correspondence and requests for materials to Amy Styring

803   or Amy Bogaard.

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816

817   **Author contributions.** A.B. conceived the study and contributed to data

818   interpretation and the writing of the manuscript; A.K.S. designed the sampling

819   protocol, carried out analyses, analysed the data and wrote the paper with A.B.; M.C.,

820   F.F., M.M.H. and A.S. contributed botanical material and data; A.M., G.S. and H.W.

821   contributed data and gave permission for analysis of material; R.M., A.K.P. and

822   J.A.W. contributed faunal material and data; G.K.N. led the statistical analysis and

823   developed the statistical models; M.C.P. and A.So. contributed human bone and

824   dentine material and data. All authors discussed the results and implications and

825   commented on the manuscript at all stages.

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828   **Figures**

829

830   **Figure 1. Geographical location of the study area. (a)** Overview of northern

831   Mesopotamia, with the locations of the palaeoclimate records of Soreq Cave, Lake

832   Van, Lake Zeribar and Lake Mirabad marked. **(b)** Location of the archaeological sites

833   Tell Sabi Abyad, Tell Zeidan, Tell Brak, Hamoukar and Tell Leilan included in this

834   study. Annual rainfall data are derived from interpolation of average monthly climate

835   data for 1960–1990, available from the WorldClim database [29].

836

837   **Figure 2. Modern cereal grain δ^{15}N values plotted against the natural log of**

838   **mean annual rainfall, colour coded by manuring level.** Lines represent a fitted

839   linear model relating cereal grain δ^{15}N values to mean annual rainfall for each

840   manuring level. Annual rainfall data are derived from interpolation of average

841   monthly climate data for 1960–1990, available from the WorldClim database [29].

842

843   **Figure 3. Archaeological cereal grain sample δ^{15}N values plotted against date.**

844   Symbol shape varies with site and symbols are colour coded by crop taxon. Points

845   outlined in black come from a single storage context. Dating of the crop samples is

846   based on stratigraphic relationships to radiocarbon-dated contexts. More details of the

847   samples are given in Supplementary Table 1.

848

849   **Figure 4. The probability of an archaeological cereal grain sample having a**

850   **manuring level m or lower plotted against site size, where (a) m = low and (b) m**

851   **= medium (right).** Symbol shape varies with site (see Figure 3 for legend). Points

852   give the posterior probability for a given cereal grain sample to have a manuring level

853   derived by multiple-imputation that is lower than m. The points are imputed in the

854   first phase of the inference using a normal linear model regressing δ^{15}N on the natural

855   log of rainfall and manuring level. Boxes give the quartiles of the fitted posterior

856   probabilities in the proportional-odds regression of manuring level on site size. The

857   fitted values are offset by site-dependent random effects. Lines show the expected

858   posterior probability that a cereal grain sample at a particular site size has manure

859   level m or lower, and displays the decrease in manuring intensity as site size

860   increases. See Supplementary Information for more detail.

861

862 **Figure 5. Archaeological cereal grain and pulse sample Δ^{13}C values plotted**

863 **against date. (a)** Barley and *Aegilops* grain samples. **(b)** Wheat grain and pulse seed

864 samples. Symbol shape corresponds to the site and symbols are colour coded by crop

865 taxon. Points outlined in black come from a single storage context. Dashed horizontal

866 lines indicate the suggested 'boundaries' between Δ^{13}C ranges indicative of crops

867 grown under poorly (low Δ^{13}C), moderately, and well (high Δ^{13}C) watered conditions,

868 based on the analysis of present-day crops [cf. 46]. *Aegilops* are plotted with barley

869 grains because they were found in a barley store and are therefore assumed to have

870 grown in the same fields as the barley.

871

872 **Figure 6. Human and faunal bone collagen and crop δ^{13}C and δ^{15}N values plotted**

873 **in relation to ellipses representing the expected distributions (mean ± 2 standard**

874 **deviations) of δ^{13}C and δ^{15}N values of individuals consuming various dietary**

875 **combinations of cereal grains, pulses and animal products (milk and/or meat).**

876 **(a)** Late Chalcolithic 2 Tell Brak (c. 4200–3900 BC); **(b)** Late Chalcolithic 3–4 Tell

877 Brak (c. 3900–3300 cal BC); **(c)** Early Bronze Age Tell Brak (c. 3000–2000 cal BC);

878 and **(d)** Early Bronze Age Tell Leilan (c. 2600–2000 cal BC).
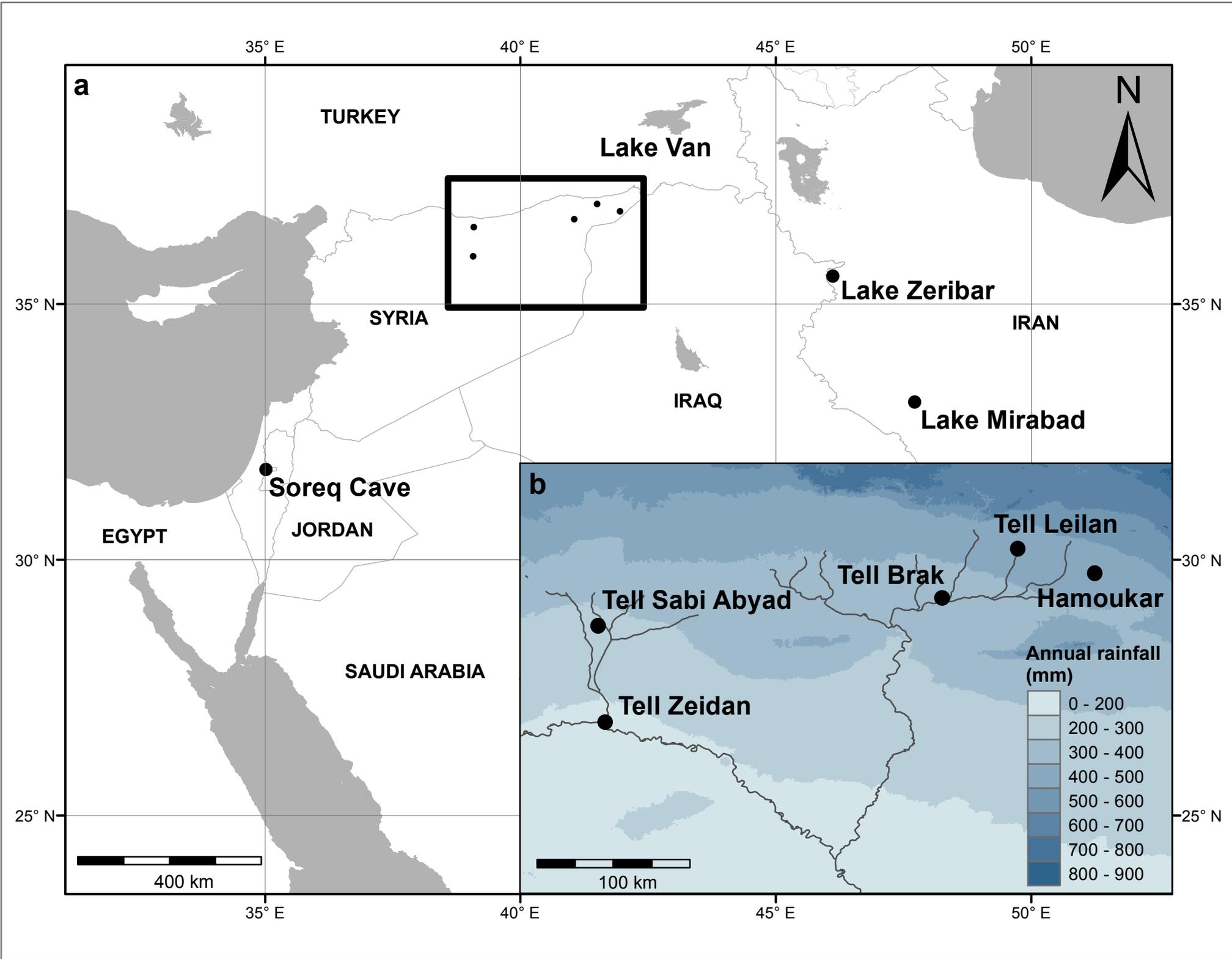
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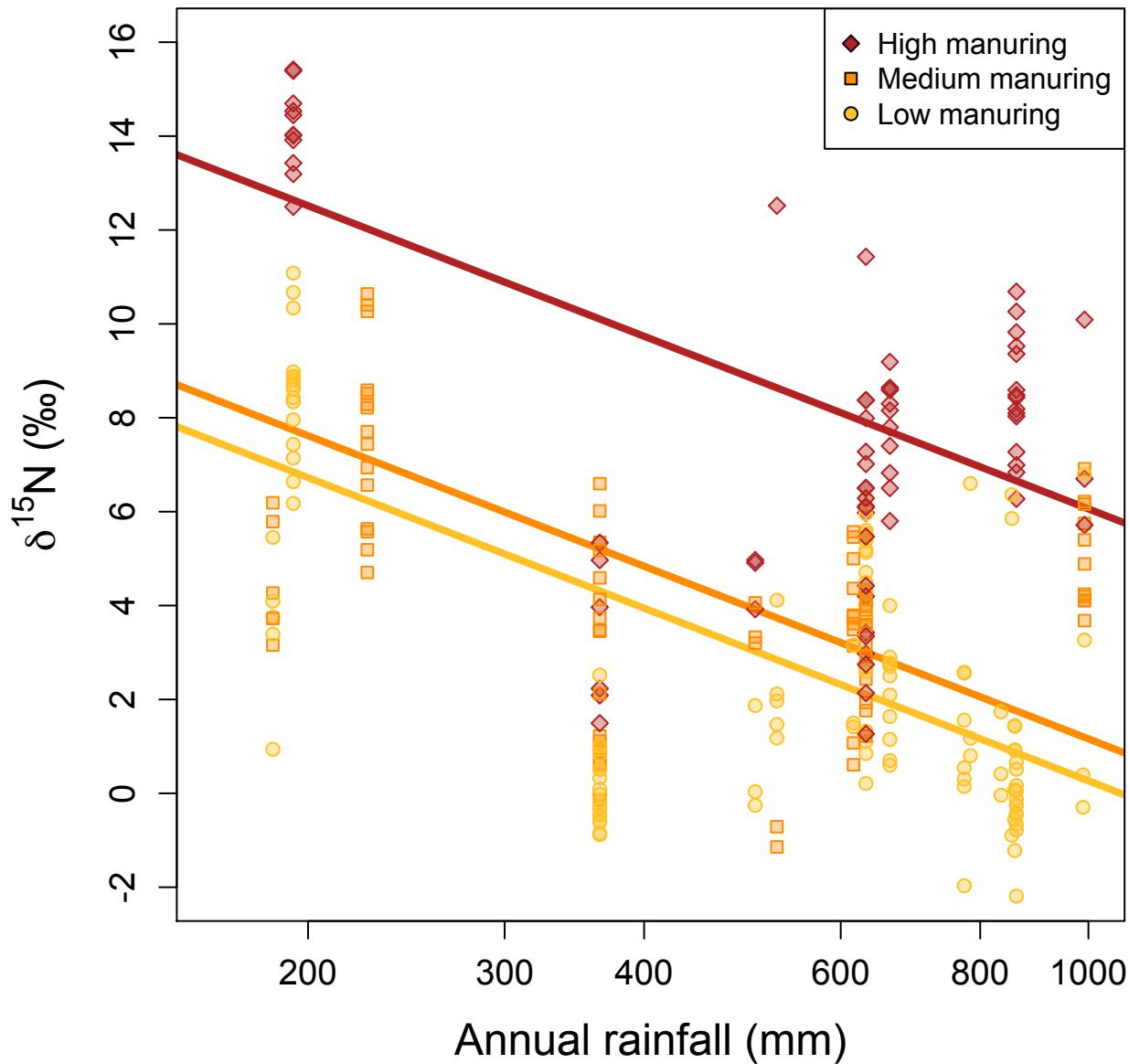
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887 **Table 1.** Details of archaeological sites, including location, chronology, settlement size and sample details. Present-day annual rainfall is derived

888 from interpolation of average monthly climate data for 1960–1990, available from the WorldClim database [29]. The date range of each

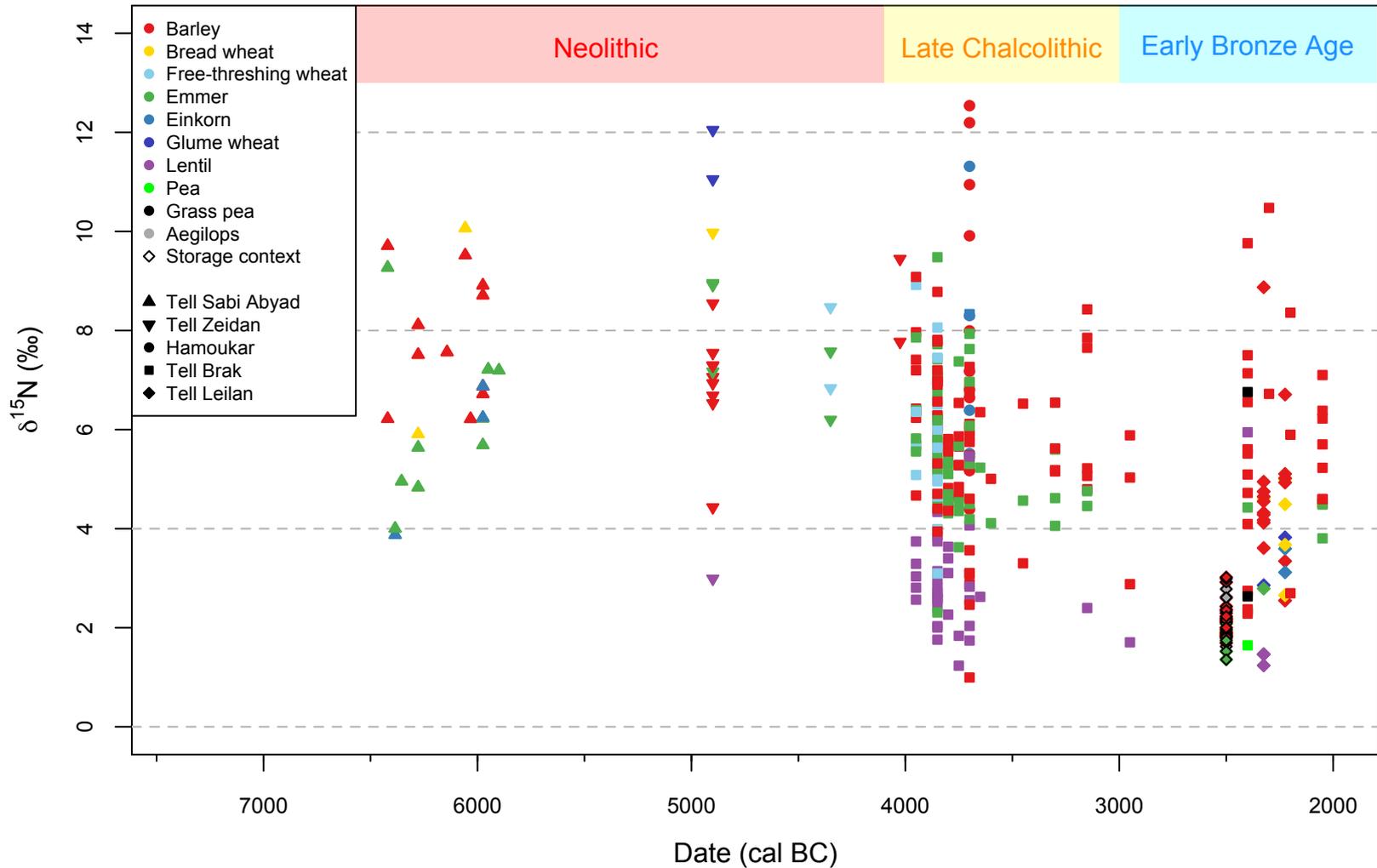889 archaeological phase is based on stratigraphic dating and radiocarbon ages.

Site	Location (latitude N, longitude E)	Present-day annual rainfall (mm)	Archaeological phase	Date (cal BC)	Settlement size (ha)	Summary of contexts	References
Tell Sabi Abyad	39.09, 36.50	280	Early Pottery Neolithic–Halaf	6700–5850	1	Domestic fills, storage bins	75
Tell Zeidan	35.94, 39.08	182	Ubaid–LC2	5300–3850	12	Pyrotechnic features and domestic contexts	54
Tell Brak	36.67, 41.06	363	LC2	4200–3900	55	Mix of workshops, storage, industrial features and monumental buildings	32, 33
			LC3–4	3900–3600	130	Public building, private households and courtyards	32, 33
			LC4–5	3600–3000	45	Large house with southern Late Uruk ceramics	32
			EJ 0	3000–2900	45	Pit cutting LC4–5 house	52
			EJ III–IV	2500–2100	70	Domestic quarters within a 'high status' household	
			EJ V	2100–2000	45	Potentially 'public building'	
Hamoukar	36.81, 41.96	445	LC	3800–3500	15	Area B: tripartite buildings, large ovens	76
Tell Leilan	36.96, 41.51	446	EJ II (Leilan IIId)	2700–2600	90	Acropolis northwest public stores; Lower Town South residential buildings	53, 55
			EJ III (Leilan IIa)	2600–2300	90	Lower Town South residential buildings	
			EJ IV (Leilan IIb)	2300-2230	90	Lower Town South residential buildings; Acropolis northwest Akkadian palace	
			EJ V (Leilan IIc)	2230-2200	0.1	Acropolis post-Akkadian four-room house	

Table 2. Details of site location, mean annual rainfall and manuring regimes for modern crop samples. Annual rainfall is derived from

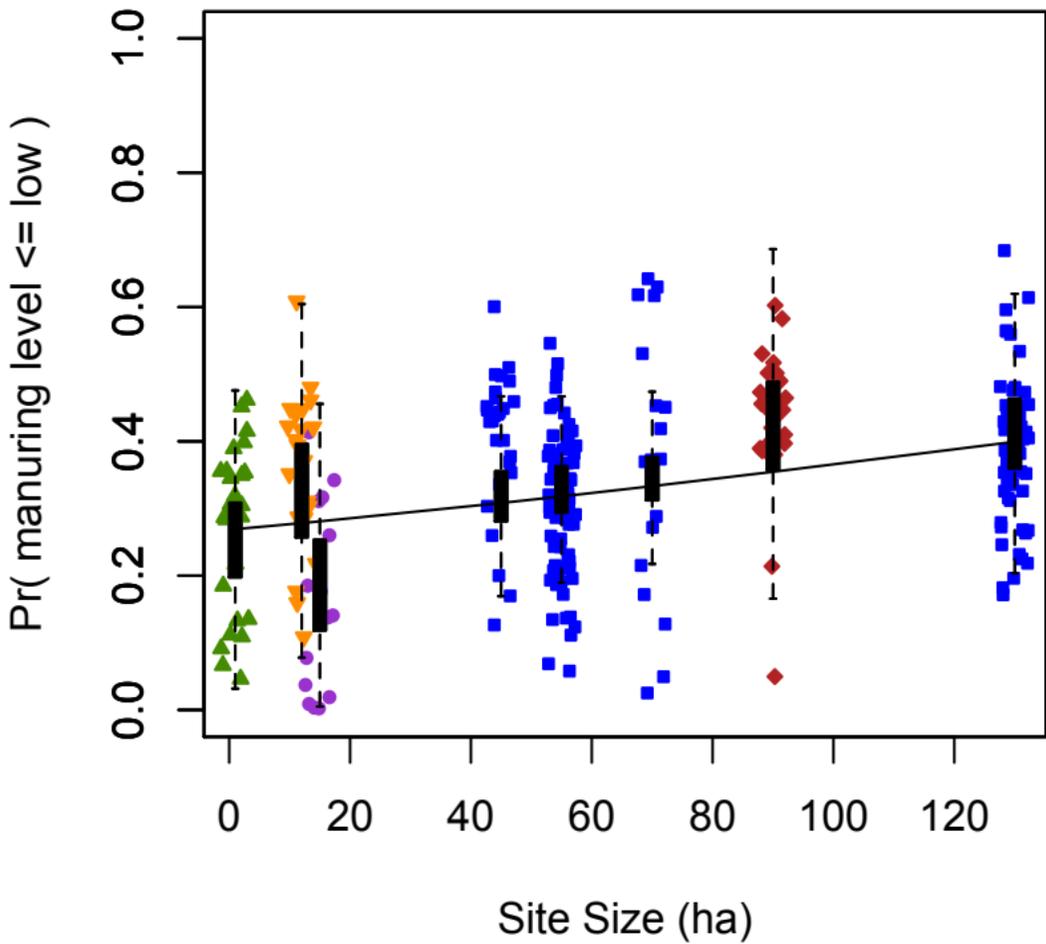interpolation of average monthly climate data for 1960–1990, available from the WorldClim database [29].

Site	Location	Country	Location (latitude N, longitude E)	Annual rainfall (mm)	Year of collection	Crop species	Manuring regimes	No. of plots
Askov	South Jutland	Denmark	55.53, 9.09	838	2007 and 2008	Two-row hulled barley, bread wheat, emmer, spelt	Low and high	28
Sutton Bonington	Nottinghamshire	UK	52.82, -1.25	632	2007 and 2008	Einkorn, emmer, spelt	Low, medium and high	55
Rothamsted Research	Hertfordshire	UK	51.8, -0.36	655	1852-2004	Two-row hulled barley, bread wheat	Low and high	22
Bad Lauchstädt	Leipzig-Halle	Germany	51.39, 11.83	503	2007 and 2008	Two-row hulled barley, bread wheat	Low, medium and high	11
Sighisoara region	Transylvania	Romania	46.41, 24.92	641	2008	Bread wheat, einkorn	Low and medium	14
Haute Provence	Lubéron/Sault region	France	44.02, 5.42	897	2013	Bread wheat, einkorn	Low	19
Lena district	Asturias	Spain	43.03, -5.76	964	2007	Spelt	Low, medium and high	16
Kastamonu	Kastomonu	Turkey	41.38, 33.70	570	2008	Durum wheat, einkorn, emmer	Low and medium	8
ICARDA	Aleppo	Syria	36.01, 36.93	419	2008	Bread wheat	Low, medium and high	42
Bellota	Ouezzane	Morocco	34.95, -5.54	703	2014	Two-row hulled barley, bread wheat	Low	6
Wadi ibn Hammad	Kerak	Jordan	31.30, 35.63	186	2007	Durum wheat	Low and medium	10
Tighirt	Sidi Ifni	Morocco	29.35, -9.43	272	2014	Two-row hulled barley	Medium	15
Amtoudi (oasis)	Guelmim	Morocco	29.24, -9.19	194	2014	Two-row hulled barley	High	11
Amtoudi (decrue)	Guelmim	Morocco	29.24, -9.19	194	2015	Two-row hulled barley, bread wheat	Low	16

(a) Pr(manuring level <= low) vs Site Size (ha); (b) Pr(manuring level <= medium) vs Site Size (ha)
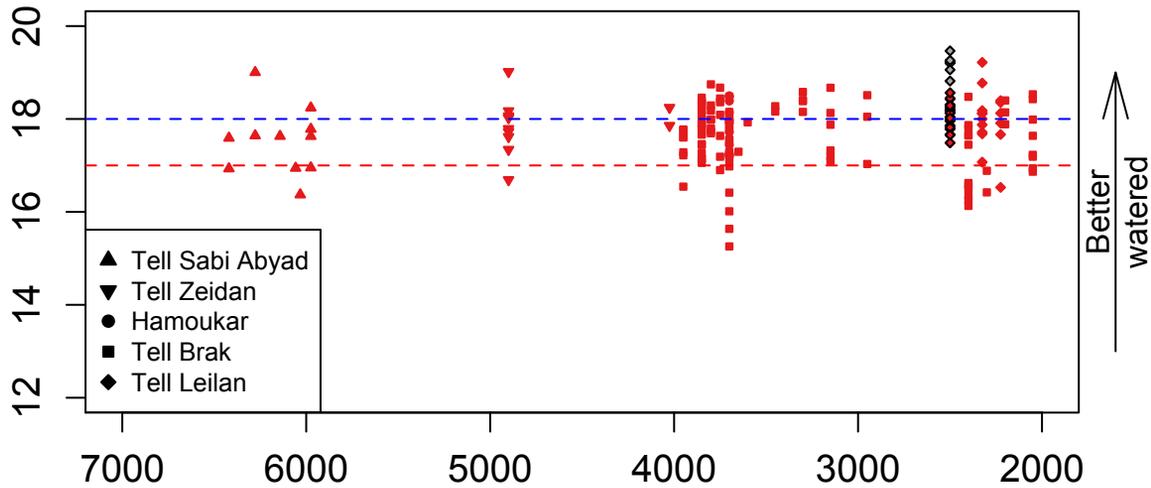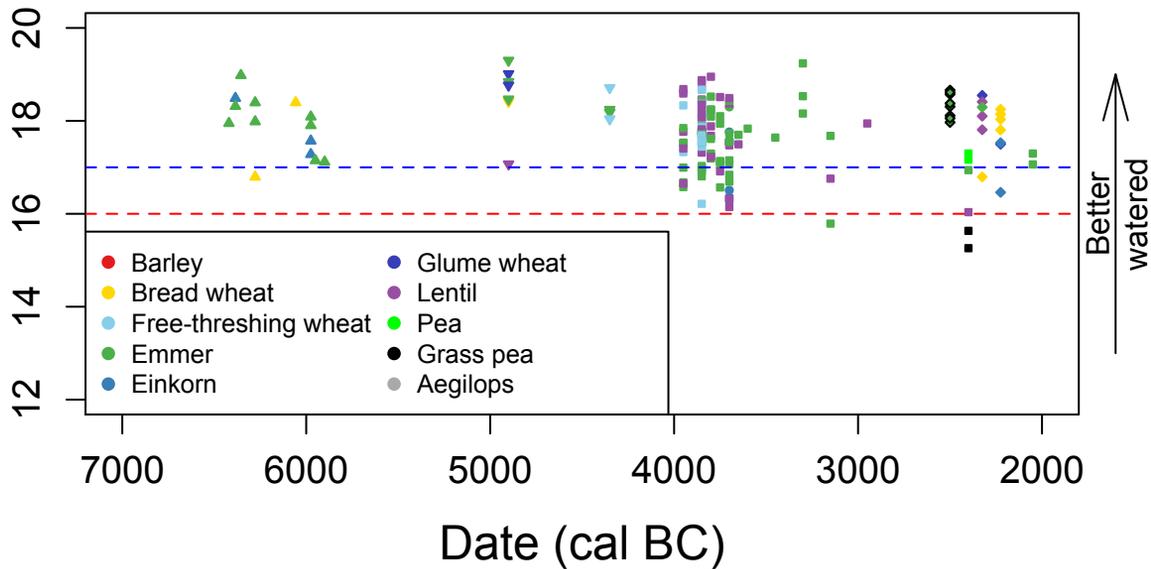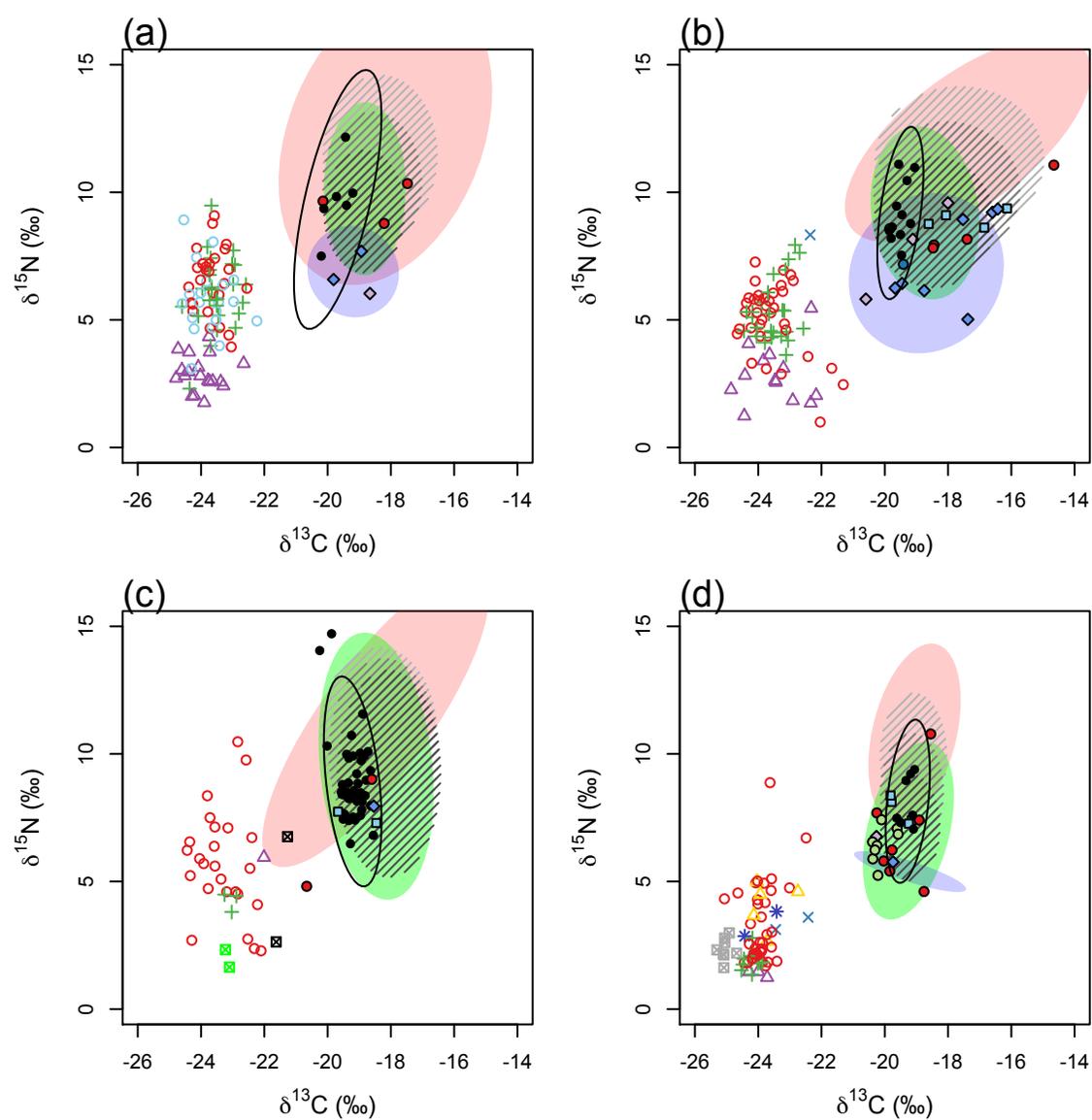
(a)

(b)

(a)

(b)

(c)

(d)

Crops
- ○ Barley
- △ Bread wheat
- ○ Free-threshing wheat
- + Emmer
- × Einkorn
- ✳ Glume wheat
- △ Lentil
- ⊠ Pea
- ⊠ Grass pea
- ⊠ Aegilops

Fauna
- ◇ Gazelle
- ● Cattle
- ◻ Sheep
- ◆ Goat
- ○ Pig

Dietary reconstruction
- ● Human
- ▨ 100% animal protein consumption
- ▨ 100% cereal grain consumption
- ▨ 100% pulse consumption
- ▨ 80% animal protein consumption
- ▨ 50% animal protein consumption
- ▨ 20% animal protein consumption