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Agricultural expansion and settlement economy in Tell Halula (Mid-Euphrates valley): A diachronic study from early Neolithic to present

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ABSTRACT

Modern Syria, and in particular the Middle Euphrates valley, has been occupied and overexploited since the beginnings of agriculture. Thus, the study of the economic and environmental characteristics of ancient settlements may offer new perspectives on the long-term effects of continuous agriculture in a fragile agroecosystem. In this work, we present a methodological framework that uses archaeological information to understand long-term effects of the extensification of agriculture in present-time arid areas. Specifically, we have compared the main economic features of a Neolithic site of the middle Euphrates, Tell Halula (ca. 10th millennium BP), with present-day data from the surrounding region. Population, crop distribution, cereal yields and arable land requirements during the first millennia after the emergence of agriculture were estimated from archaeological data and compared with a compilation of present-time official statistics and data derived from a field survey. We observed a trend towards a cereal-based farming during the Neolithic, associated to a decrease in the diversity of wild florae. This was accompanied by a growth in population during the earliest phases of the settlement (8200-7000 cal BCE), followed by a decline in population in the late phases (7000-5400 cal BCE), probably as a consequence of exceeding the capacity of the agroecosystem. A comparable situation to that found in early phases of Tell Halula was observed in modern communities, showing similar growth rates and a strong focus on cereal crops.

1. Introduction

The Near East and, particularly, the Fertile Crescent, where Western agriculture originated at the beginning of the Holocene, is currently facing rapid population growth, degradation of its natural resources, and increasing dependency on food imports (Rodriguez and Manners, 1996). With an average population growth rate of 2% (C.I.A. 2010), modern Syria is a good example of this situation. The steady increase in food demand, together with the limited availability of arable land of low productivity, are putting further pressures on the fragile Mediterranean ecosystem, therefore accentuating degradation of natural resources. In addition to the demographic and social changes that threaten the development of this region, global climate change is challenging even more the present situation (IPCC, 2001).

Agriculture was adopted independently in various parts of the world during the Holocene, a period of global warming that followed the end of the last Ice Age, at about 11,600 cal. BP, suggesting an important role of climate in this process (see Balter, 2007; Ferrio et al., 2011). In the Near East, palaeo-environmental records indicate a reduction in steppe species and forest expansion during the Early Holocene, and higher water availability than in present times (see refs. in Ferrio et al., 2011; Riehl, 2008; Willcox et al., 2009). Consequently, the particular climatic conditions for this period could have been crucial for the success of early-farming communities. On the other hand, the adoption and spread of agriculture sets the starting point for significant human-induced impacts on natural ecosystems (e.g. Hill, 2004; Yasuda et al., 2000), although resource limitation due to land degradation was not likely to occur before the Bronze Age (see e.g. Deckers and Riehl, 2008).

Although current environmental and economic constraints may differ from those faced by early farmers, archaeological records offer an unique opportunity to study long-term effects of agriculture (Butzer, 2005). Thus, understanding how demographic and/or

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environmental changes affected settlements' economy at the beginnings of agriculture may help to face current challenges in the Fertile Crescent (Araus, 2004). In this regard, ethnoarchaeology offers a link between past and modern agricultural societies (London, 2000). Until now, the main focus of this discipline has been to solve specific archaeological questions (Hillman, 1973; London, 2000; Ur, 2002; Wilkinson, 1994). The aim of this work, however, focuses on a wider issue, that is, to understand long-term effects of cereal-based farming in present-time arid areas. Specifically, we aim at comparing, from a diachronic perspective, the main economic features (i.e. demography and crop production) of Tell Halula, a 10th millennium BP site on the middle Euphrates, with present-day information from its surrounding region. Population, crop distribution, cereal yields and arable land requirements, among others, were estimated from archaeological records and compared with a compilation of official statistics and data derived from a field survey performed *in situ* for the area.

2. Materials and methods

2.1. Area of study

We focused our research on the area around the archaeological site of Tell Halula (36°25′N, 38°10′E, 337 m.a.s.l.), placed in the Mid-Euphrates region (Governorate of Rakka, Syria) about 105 km east of Aleppo and 25 km northwest of Membij (Fig. 1). Tell Halula is a representative site for the beginnings of agriculture, and comprises (to date) three main excavated periods: Middle and Late Pre-Pottery Neolithic B (M-PPNB, 8200-7500 cal BCE and L-PPNB, 7500-7000 cal BCE, respectively), Early Pottery Neolithic (E-PN, Pre-Halaf, 7000-6100 cal. BCE), and Late Pottery Neolithic (L-PN, Proto-Halaf and Halaf, 6100-5400 cal. BCE). Agriculture was practised continuously in the region from its origins to the late Roman-Byzantine period, and perhaps even reaching the arrival of Muslims (Arab, 2008). Since then, and till the second half of the 19th century, the region remained unsettled, being used only by Bedouins for grazing. It was not until the 20th century when some of the tribes started a transformation from herders into farmers and founded current communities (Arab, 2008). The area is characterised by an steppe climate, with an average annual rainfall of 260 mm, mean temperature of 17.9 °C, and a mean annual ratio between precipitation and evaporative demand of 0.16 (De Pauw et al., 2001).

2.2. Archaeological data

Archaeological data were compiled from bibliographical sources and unpublished results. The aim was to provide information about the structure and socio-economics of ancient farming communities, including demography, crop distribution, vegetation changes and the estimation of past yields of the main crops cultivated. Plant remains were recovered by flotation from the archaeological sediment and identified based on morphological attributes, as described elsewhere (Buxó, 1997; Buxó and Rovira, in press). The recovery of plant remains was performed systematically in all settlement layers and structures, covering in each period various archaeological contexts, such as domestic fires, cooking ovens, room floors and levels of rubble from housing structures and pits (See summary in Table 1). To avoid biased results due to differential preservation of vegetative remains, only plant remains representing complete seeds or fruit structures were considered for the present study. In the case of weeds, we focused on the taxa representing 1% or more of the total remains in at least one of the periods studied (34 out of 104 taxa, 94% of weed remains). In order to assess the influence of agriculture consolidation on weed florae, the remains were classified either as "cereal weeds" (i.e. those taxa commonly associated to cereal crops) and "other wild species". Additionally, three different biodiversity indexes were calculated for the weed dataset: species richness (S), defined as the total number of taxa per period; diversity (H), calculated from the frequency of presence (ubiquity) of each taxon (p_i), according to Shannon–Wiener index of diversity (Pielou, 1966); and evenness (H′), derived from H and S:

$$H = -\sum_{i=l}^{n} p_i \ln(p_i) \quad (1)$$

$$H' = \frac{H}{\ln(S)} \quad (2)$$

Cereal yields for barley and naked wheat were estimated from the stable isotope composition of fossil grains, as described

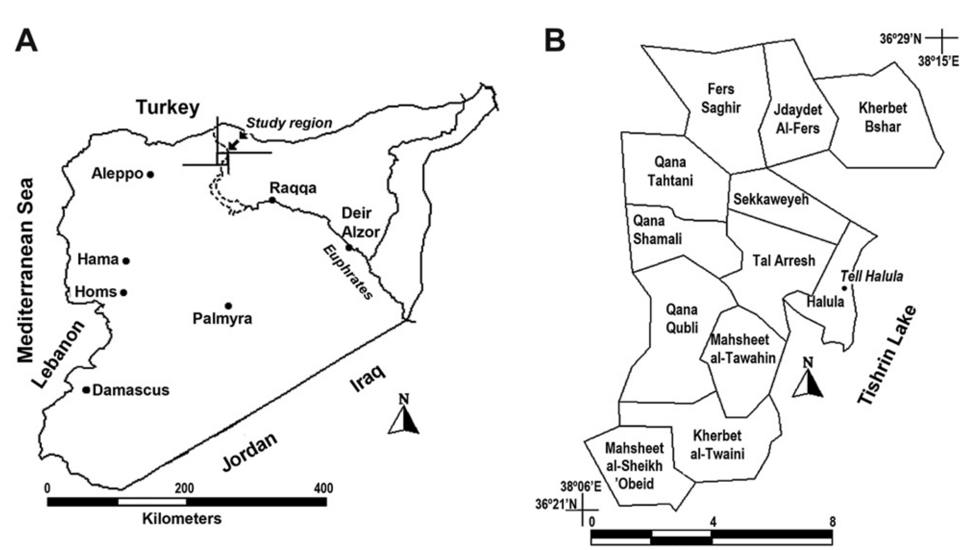

Fig. 1. A) Geographical location of the area of study and B) detail of the communities included in the field survey reported in Arab (2008), indicating the location of the archaeological site, Tell Halula. Redrawn from Ferrio et al. (2007).

Table 1
Summary statistics of plant remains recovered in the site for each period.

	Middle pre-pottery Neolithic B	Late pre-pottery Neolithic B	Early pottery Neolithic	Late pottery Neolithic
Sediment volume (liters)	813	565	368	1354
Number of samples	77	19	31	65
Number of seeds/fruits	1480	1379	279	770
Indeterminate remains	1275	520	821	36

elsewhere (Araus et al., 1999b, 2007). For emmer wheat, yields were estimated from naked wheat and barley data by correcting for the yield ratio between emmer and either naked wheat (0.64 ± 0.19; Stallknecht et al., 1996) or barley (1.30 ± 0.03; Reynolds, 1997), and taking the average between both estimates. Following Aguilera et al. (2008), grain yield values were further corrected by the smaller grain size observed in the archaeological context when compared to present values (22 mg and 35 mg for past and present, respectively) in the area (Araus et al., 2007; Ferrio et al., 2004). Although determining grain size from charred material is constrained by the effect of charring on grain dimensions (see e.g. Boardman and Jones, 1990; Ferrio et al., 2004), our correction was based on the maximum observed values in relatively well preserved grains (i.e. not strongly distorted by charring), and after applying the models developed by Ferrio et al. (2004) to account for the effect of charring. The settlement's population in the past was inferred from estimates of built surface and applying ethno-archaeological criteria derived from population density in present villages from the Near East, following Aurenche (1981) and Deckers and Riehl (2008). Age and sex distribution was based on the anatomical classification of human remains recovered during excavation, as detailed in Guerrero (2006). Due to the scarcity of remains, this was only possible for the PPNB as a whole. The population growth rate was obtained by a regression on simulated stable populations generated from 45 reference life tables with pre-industrial mortality:

$$\text{Growth rate}(r) = a + bP_{(5-19)^c} \tag{3}$$

where $a = -0.05389$, $b = 0.12555$, $P_{(5\text{-}19)} =$ the ratio of immatures (individuals between 5 and 19 years old) to the total skeletal population 5 + years old, and $c = 0.47788$(for more details of this procedure readers are referred to Bocquet-Appel, 2002; Bocquet-Appel and Masset, 1977). It was possible to directly estimate the

Table 2
Classification of archaeobotanical taxa of cultivated species into main groups, including number and ubiquity (% of sediment samples where a given taxon is present) of complete seeds/fruits recovered.

Group	Taxa included	Number of seeds/fruits				Ubiquity (% of samples)			
		M-PPNB	L-PPNB	E-PN	L-PN	M-PPNB	L-PPNB	E-PN	L-PN
Emmer wheat	*Triticum dicoccum*	193	90	35	318	49.3	47.4	29.0	47.7
	T.dicoccum/monococcum	2	–	–	6	1.3	–	–	7.7
	T. cf. *dicoccum*	1	9	–	–	1.3	15.8	–	–
Naked wheat	*T. aestivum/durum*	158	458	4	66	44.0	68.4	12.9	26.2
Wheat (others)	*T. monococcum*	4	–	1	25	4.0	–	3.2	10.8
	T. cf. *monococcum*	4	–	–	11	2.7	–	–	4.6
	Triticum sp.	14	20	4	7	9.3	21.1	9.7	4.6
Hulled barley	*Hordeum distichum*	56	35	23	232	6.7	21.1	22.6	33.8
	H. cf. *Distichum*	3	5	–	2	1.3	5.3	–	1.5
	H. spontaneum/distichum	49	–	–	2	5.3	–	–	3.1
	H. vulgare var. *vulgare*	28	8	12	11	17.3	15.8	12.9	6.2
Barley (others)	*H. vugare* var. *nudum*	2	8	2	6	2.7	15.8	3.2	4.6
	H.spontaneum	15	2	–	–	5.3	5.3	–	–
	H. cf. *spontaneum*	1	15	–	–	1.3	10.5	–	–
Cereal (others)	*Hordeum/Triticum*	5	–	–	–	2.7	–	–	–
	Aegilops crassa	1	–	2	98	1.3	–	3.2	13.8
	Aegilops sp.	2	2	20	16	2.7	5.3	25.8	16.9
	cf. *Aegilops* sp.	12	–	–	–	1.3	–	–	–
	Secale sp.	0	3	–	–	0.0	5.3	–	–
	cf. *Secale* sp.	1	1	–	–	1.3	5.3	–	–
All cereals		**551**	**656**	**103**	**800**	**72.0**	**89.5**	**58.1**	**73.8**
Lentil	*Lens orientalis/culinaris*	20	198	1	–	14.7	15.8	3.2	–
	Lens sp.	40	22	1	–	20.0	26.3	3.2	–
	cf. *Lens* sp.	3	1	–	–	2.7	5.3	–	–
Pea	*Pisum* sp.	8	6	8	3	2.7	5.3	16.1	4.6
	cf. *Pisum* sp.	2	1	–	–	2.7	5.3	–	–
	Pisum/Lathyrus	–	1	–	–	–	5.3	–	–
Broadbean	cf. *Vicia faba*	–	–	1	1	–	–	3.2	1.5
Other legumes	*Lathyrus sativus*-type	1	–	–	–	1.3	–	–	–
	Lathyrus sp.	3	–	–	–	4.0	–	–	–
	Fabaceae	1	–	–	–	1.3	–	–	–
All legumes		**118**	**269**	**16**	**71**	**52.0**	**52.6**	**32.3**	**24.6**
Fiber crops	*Linum usitatissimum*	**15**	**10**	**3**	**61**	**10.7**	**5.3**	**9.7**	**18.5**
	Capparis sp.	18	25	–	4	6.7	10.5	–	4.6
	Ficus sp.	3	3	1	1	2.7	5.3	3.2	1.5
	cf. *Ficus* sp.	1	1	1	1	1.3	5.3	3.2	1.5
	Pistacia sp.	1	1	–	–	1.3	5.3	–	–
	Vitis vinifera subsp. *sylvestris*	2	–	–	–	1.3	–	–	–
All fruit-trees		**25**	**30**	**2**	**6**	**10.7**	**15.8**	**6.5**	**6.2**
Total crops		**709**	**965**	**124**	**938**	**81.3**	**89.5**	**61.3**	**78.5**

Total values for each category are indicated in bold characters.

growth rate from the $P_{(5-19)}$, since this proportion of immatures provides information on the shape of the age pyramids, which is basically an effect of the birth rate of a population; so that, in a growing population the proportion of immatures is high, and in a declining one it is low (Johansson and Horowitz, 1986; Sattenspiel and Harpending, 1983). Required cultivated land was calculated assuming an average requirement of 300 kg $people^{-1}\ yr^{-1}$ to fulfil nutritional needs, plus *ca.* 10% reserved for sowing (Araus et al., 2003; Wilkinson, 1994). Finally, we estimated land requirements per site and inhabitant from population and yield. It should be noted that, given the number of assumptions required, the absolute values derived from these calculations should be taken with caution, although they may be helpful at identifying population and land-use trends over time.

2.3. Contemporary data and field survey

Contemporary records were derived from information published by the Syrian Ministry of Agriculture and Agrarian Reform (The Annual Agricultural Statistical Abstract, 1996), data provided by the Membij Farmers Union and Department of Agriculture, and from a field survey performed in the framework of the EU project MENMED in twelve communities in the surroundings of the archaeological site (Arab, 2008; Fig. 1b). Further methodological details about the survey can be found in Arab (2008). Total production for each crop was calculated as the product of cultivated area and average yield for each crop in 2004 as reported in Arab (2008). Required cultivated land was calculated as described in section 1.2.

3. Results

3.1. Crop distribution

In the Neolithic site of Tell Halula, naked wheat (*Triticum aestivum/durum*), emmer (*Triticum dicoccum*) and hulled barley (*Hordeum vulgare/distichum*) were most likely the main cultivated crops, together with two pulses, lentil (*Lens culinaris*) and pea (*Pisum sativum*), and a single oil-and-fiber crop, flax (*Linum usitatissimum*) (Table 2, Fig. 2). Of minor importance were other cereals, either gathered or cultivated (*T. monococcum*, *H. vulgare* var. *nudum*, *Secale* sp., *Hordeum spontaneum*, *Aegilops* sp.), as well as some fruit-trees, probably harvested from natural vegetation, such as *Amygdalus* sp., *Capparis* sp., *Ficus* sp., *Pistacia* sp. and *Vitis* sp. The occurrence (ubiquity) of cereal crops remained fairly constant, being present in 94% of the samples with crop remains on average, whereas the

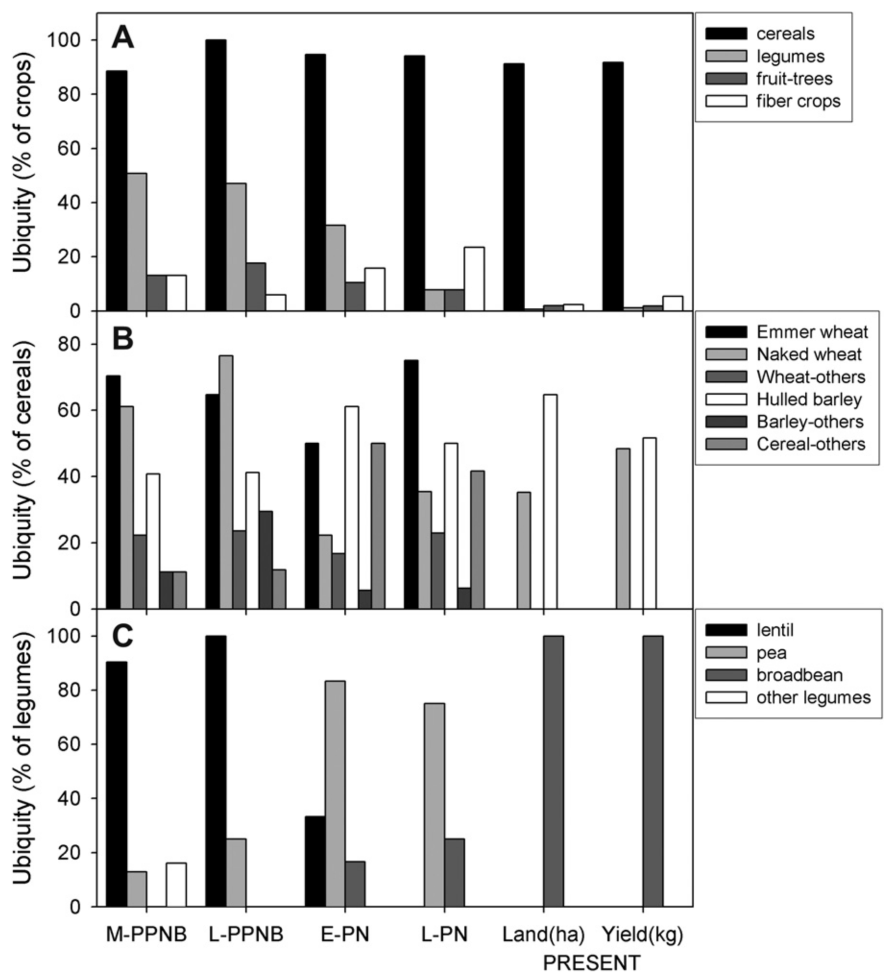

Fig. 2. Changes over time of the distribution of different crops in Tell Halula and comparison with present distribution. Archaeological values are based on the relative frequency of presence (ubiquity) of plant reproductive propagules (seeds, fruits and analogue organs) found for each species, excluding fragments and vegetative parts. Values are expressed in relative terms, i.e. respect to the number of samples including remains from each category: A) crops, B) cereals and C) legumes. Present values are based either on land use (area) or total annual production per crop (yield) in 2004. M-PPNB and L-PPNB stand for Middle and Late Pre-Pottery Neolithic B, respectively; E-PN and L-PN stand for Early (Pre-Halaf) and Late (Proto-Halaf and Halaf) Pottery Neolithic.

occurrence of fruits and legumes decreased over time (Fig. 2A). In contrast, the relative presence of fiber crops (flax) increased from about 10% (PPNB) to *ca*. 20% (PN). Among cereals, the two main forms of domesticated wheat (naked wheat and emmer) were dominant throughout the studied period, but their relative frequency decreased from 68% (PPNB) to 46% (PN), whereas hulled barley increased from 41 to 56% (Fig. 2B). A comparable increase was also found for the pool of other cereals (from 11 to 46%), mainly through the sudden rise in the frequency of *Aegilops* sp. (from less than 1% during the PPNB up to 46% during PN). Regarding legumes, lentil was clearly dominant in PPNB phases (95%), but was replaced by pea (79%) and broadbean (21%) in PN (Fig. 2C).

Currently, the landscape in Halula region is dominated by cereal crops (with 91% of total arable land) mainly rainfed barley (59% of land) and wheat (32%, 22% of which under irrigation) (Fig. 2). Irrigated land covers about 11% of the total cultivated area, and is mainly dedicated to wheat, cotton and broadbean (with 65%, 22% and 6% of irrigated land, respectively) (Fig. 2A). The dominant fruit-trees are olive, pistachio, almond and grapevine, altogether amounting to 2% of arable land. Referring these values in terms of annual production for each crop provided similar results (Fig. 2A–C). Among cereals, however, the greater average yield of wheat compared with barley resulted in almost the same contribution of both species to the regional economy (52% and 48% of cereal production for barley and wheat, respectively), despite the greater relevance of barley in terms of land use (65% of cereal land) (Fig. 2B).

3.2. Weed assemblages

The total number and ubiquity of reproductive structures of the most abundant weeds and shrubs found in the archaeobotanical record of Tell Halula is presented in Table 3. The ubiquity of cereal-associated weeds increased over time from about 45% in E-PPNB to 71% in L-PN. A similar increase was found for other wild species, rising from 52% during the PPNB to 62% in PN phases. Nevertheless, the ratio between cereal-associated weed remains and other wild species increased over time, from 0.4 to 1.8 in terms of number of seeds (Table 3), and from 0.9 to 1.1 regarding their ubiquity (Table 3, Fig. 3A). The ratio between crop and weed remains also increased over time when the total number of seeds was considered (see Tables 2 and 3), but decreased in terms of relative ubiquity, from 1.4 in the PPNB to 0.8 in the PN. Species richness (S), diversity (H) and evenness (H') decreased from PPNB to PN phases as a result of a decline in the number of taxa, together with an increasing dominance of the most abundant species.

3.3. Cereal yields

Yield estimates for naked wheat and barley crops in the Neolithic site of Tell Halula were not far from present yields attained under rainfed conditions in the Halula region (Table 4), although a declining trend in grain yield from M-PPNB to E-PN was found for wheat. Overall, however, past cereal yields were lower than the current average for rainfed cereals, result attributable to

Table 3
Number of seeds and ubiquity of archaeobotanical taxa of weeds typically associated to winter cereal crops and other herbs and shrubs. This account includes only complete remains of seeds and fruits, and excludes very very rare taxa, i.e. those with abundances below 1% in all the studied periods.

Taxon/Grup	Number of seeds/fruits				Ubiquity (% of samples)			
	M-PPNB	L-PPNB	E-PN	L-PN	M-PPNB	L-PPNB	E-PN	L-PN
Androsace maxima	1	5	–	11	1.3	5.3	–	10.8
Avena sp.	10	10	8	13	8.0	5.3	16.1	12.3
Bellevalia sp.	5	1	2	33	6.7	5.3	6.5	16.9
Bromus sp.	25	10	10	17	12.0	15.8	16.1	15.4
Galium sp.	9	5	6	7	6.7	10.5	19.4	7.7
Glaucium aleppicum-type	6	19	–	–	4.0	10.5	–	–
Hordeum cf. murinum	40	36	4	5	4.0	5.3	3.2	4.6
Hordeum murinum	12	9	–	–	6.7	10.5	–	–
Lithospermum arvense-type	5	–	2	30	1.3	–	3.2	10.8
Lolium sp.	89	60	62	251	14.7	26.3	32.3	61.5
Papaver cf. dubium/rhoeas	–	56	1	–	–	5.3	3.2	–
Papaver cf. somniferum	–	23	–	–	–	5.3	–	–
Papaveranum cf. *glaucium*	19	–	–	–	1.3	–	–	–
Poaceae	51	64	3	4	16.0	31.6	9.7	4.6
Polygonum sp.	20	2	3	–	5.3	5.3	9.7	–
Silene sp.	21	10	9	9	10.7	31.6	9.7	9.2
Vicia sp.	2	–	8	–	2.7	–	9.7	–
Cereal weeds	**315**	**310**	**118**	**380**	**45.3**	**52.6**	**51.6**	**70.8**
Arenaria sp.	11	14	1	–	4.0	15.8	3.2	–
Arnebia decumbens-type	22	56	32	135	9.3	5.3	16.1	43.1
Arnebia sp.	36	167	34	–	10.7	36.8	29.0	–
Asperula sp.	–	–	–	6	–	–	–	6.2
Asteraceae	15	2	1	–	6.7	10.5	3.2	–
Astragalus sp.	181	78	1	18	14.7	21.1	3.2	13.8
cf. Helianthemum sp.	–	152	–	–	–	5.3	–	–
Echinaria sp.	–	–	–	6	–	–	–	3.1
Eremopyron sp.	78	10	–	–	8.0	10.5	–	–
Helianthemum sp.	–	43	–	–	–	5.3	–	–
Heliotropium sp.	74	127	19	1	13.3	31.6	12.9	1.5
Linum sp.	78	68	2	1	10.7	21.1	3.2	1.5
Lithospermum tenuiflorum	268	43	17	40	36.0	36.8	32.3	26.2
Polygonum/Cyperus	30	–	–	–	1.3	–	–	–
Scirpus sp.	17	–	–	–	1.3	–	–	–
Teucrium sp.	16	15	2	–	5.3	10.5	6.5	–
Trifolium sp.	37	33	–	–	8.0	26.3	–	–
Other wild species	**863**	**808**	**109**	**207**	**52.0**	**52.6**	**61.3**	**63.1**
Total weeds	**1178**	**1118**	**227**	**587**	**66.7**	**57.9**	**83.9**	**86.2**

Total values for each category are indicated in bold characters.

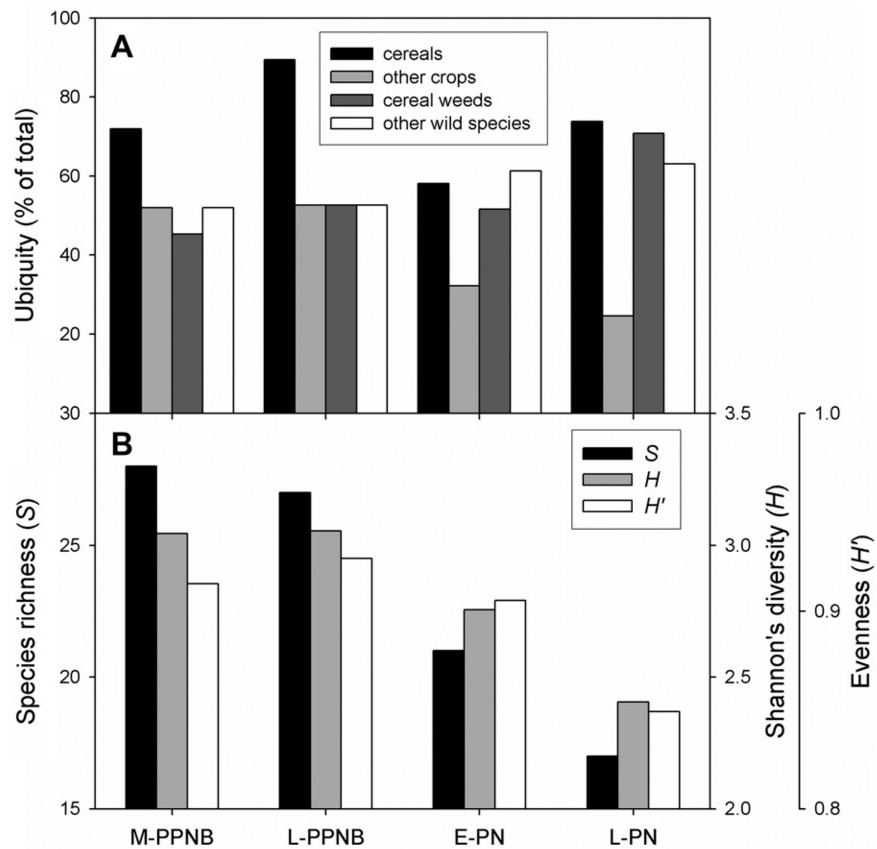

Fig. 3. Changes over time of A) the frequency of presence (ubiquity) of cereals, other cultivated plants and wild plant species (weeds), respect to the total number of samples studied, and B) biodiversity indicators for weed assemblages in Tell Halula. *S*, number of taxa; *H*, Shannon's diversity index; *H′*, evenness. M-PPNB and L-PPNB stand for Middle and Late Pre-pottery Neolithic B, respectively; E-PN and L-PN stand for Early (pre-Halaf) and Late (Proto-Halaf and Halaf) Pottery Neolithic.

the contribution of the less-yielding emmer wheat, still a major crop during the Neolithic.

3.4. Population and land requirements

The inferred population in Tell Halula, based on settlement size and ethnoarchaeological criteria, decreased from 355 to 1420 inhabitants during M-PPNB to 275–1100 inhabitants in L-PN, considering a range of population density of 50–200 inhabitants ha^{-1} (Table 5). Population estimates were in the same range as present-time values for settlements across the twelve communities studied in 1994 (Table 5). Nevertheless, the average size of the communities grew notably for the period 1994–2004 (40.6% of increase) and, thus, the population per settlement was considerably higher in 2004, but still within the confidence limits of archaeological data.

Taking into account population and yields inferred in the past (Table 4), we obtained an estimation of the required cultivated area per person as well as for the whole settlement during the Neolithic period (Table 5). The resulting estimates for land requirement per person and per site were again in the range of those obtained for present conditions. Estimated land requirements for 2004 were in the range of land actually cultivated, but exceeded the average values in poor-yielding years. In order to estimate land actually cultivated per person and according to official statistics from the region (Arab, 2008) we assumed that the cultivated land around each community did not increase significantly from 1994 to 2004 and, on average, exceeded the nutritional requirements of the population (Table 5).

The population distribution in age classes during the PPNB was characteristic of a community with a short life expectancy, although with a high fertility,a fast growing rate, and a high child mortality (which might be around 30%, according to Guerrero, 2006 and Guerrero et al., 2008) (Table 6). Thus, the percentage of children under 10 years old (over 40%) was higher than in present times for the region (31%). Estimated population growth was 3%,

Table 4
Comparison between estimated yields for major cereal crops at the archaeological site of Tell Halula and at present in the Halula region. Present values are for rainfed crops.

Period	Yield ($t\ ha^{-1}$)			
	Naked wheat	Barley	Emmer wheat[b]	Cereal yield[c]
M-PPNB	1.2 (0.7–1.8)[a]	0.7 (0.4–1.0)[a]	0.8 (0.7–1.0)	0.9 (0.6–1.2)
L-PPNB	1.1 (0.7–1.5)[a]	0.4–1.0?	0.8 (0.7–1.0)	1.0 (0.7–1.4)[d]
E-PN	1.0 (0.7–1.3)[a]	0.7 (0.6–0.9)[a]	0.8 (0.6–1.0)	0.8 (0.6–1.0)
1994–2004		1.1 (0.3–2.4)[e]		
2004	1.5 (1.2–1.7)[f]	1.1 (0.4–1.6)[f]		1.3 (0.3–2.4)

[a] Estimated from carbon isotope discrimination of fossil grains. Original data from Araus et al. (1999a,b, 2007), corrected for potential grain size according to Aguilera et al. (2008).
[b] Estimated by applying a correction to naked wheat and barley yields, according to Stallknecht et al. (1996) and Reynolds (1997), respectively.
[c] Weighted mean based on the relative contribution of each major cereal crop, according to the proportion of seed remains and cultivated land, for archaeological and present data, respectively (see Fig. 1).
[d] Estimated using the same barley yields as in M-PPNB.
[e] Average, minimum and maximum yields in Halula region for the period 1994–2004. Data from Arab (2008).
[f] Average, minimum and maximum yields across communities in Halula region in 2004 (Arab, 2008).

Table 5
Comparison between estimated population and land requirements for the archaeological site of Tell Halula and present values in the Halula region. Estimated range for the archaeological site, mean and range for present values.

Period	Settlement size (ha)	Settlement population[a]	Cultivated land required[b]		Land actually cultivated[c]	
			(ha inhabitant^{-1})	(ha site^{-1})	(ha inhabitant^{-1})	(ha site^{-1})
M-PPNB	7.1	355–1420	0.24–0.49	86–695		
L-PPNB	7.1	355–1420	0.22–0.43	77–613[d]		
E-PN	6.8	340–1360	0.32–0.49	107–672		
L-PN	5.5	275–1100	0.32–0.49	87–543[e]		
1994[f]		655 (400–1167)	0.25 (0.12–1.09)	319 (50–1273)	1.01 (0.21–1.93)	668 (94–1664)
2004[f]		921 (562–1640)	0.25 (0.12–1.09)	448 (70–1789)	0.72 (0.15–1.38)	668 (94–1664)

[a] Neolithic population estimated from settlement size, taking a range in population density from 50 to 200 inhabitants ha^{-1} (Aurenche, 1981; Deckers and Riehl, 2008).
[b] Cultivated land required assuming an average requirement of 300 kg people^{-1} yr^{-1} to fulfil nutritional and sowing needs (Araus et al., 2003). For the archaeological site, the standard deviation interval of estimated cereal yields was used (see Table 2). For present times, we used average and range for cereal yields (Table 2).
[c] Land actually cultivated per site based on data from 2004 (Arab, 2008).
[d] Assuming the same population size as in M-PPNB.
[e] Assuming the same required land per inhabitant as in E-PN (i.e. the same average cereal yields).
[f] Average and range of values across all communities in the Halula region (Arab, 2008).

whereas average annual growth in the Halula region was about 4% for the period 1994–2004 (Arab, 2008; Guerrero, 2006). Regarding sex classes, the proportions were comparable to those found in present times, although archaeological records should be taken with caution due to the high proportion of remains from adult individuals impossible to allocate to either sex class.

4. Discussion

4.1. Agricultural consolidation during the Neolithic

Overall, we found a wider variety of crops during the earlier phases of the settlement that shifted progressively towards a cereal-based economy (see Fig. 2). Meanwhile, harvesting of wild material (fruits, nuts and wild cereals) almost disappeared. The possible expansion of the area dedicated to agriculture should have been necessarily devoted to extensive crops requiring relatively low labour efforts, such as cereals (Hillman, 1973; Wilkinson, 1994). This hypothesis is partly confirmed by a significant reduction in legume cultivation from PPNB to PN (Fig. 2). Furthermore, an expansion of cultivated area would force using less fertile soils as cultivable patches became less abundant. This may explain the reduction in cereal yields from PPNB to PN, as estimated from the carbon isotope composition of fossil grains. Since our yield estimates are based on individual grain properties, the observed decline suggests that the level of terminal water stress (i.e. after flowering) in naked wheat was higher during the PN than during the PPNB, whereas water availability remained unchanged, but low, for barley. Probably, barley was displaced from the better soils in favour of wheat already at the beginning of agriculture adoption (Aguilera et al., 2008; Ferrio et al., 2005; Jacobsen and Adams, 1958). Nevertheless, and even after applying a correction for grain size, past yields seem comparable to those attained at present, in spite of recent agronomic and genetic advances. In this regard, the likely negative impact of lower pre-industrial CO_2 levels on grain yields still remains a subject of investigation (Sage, 1995). The declining trend through Neolithic in the yields of naked wheat, together with the progressive increase of seed remains of more drought-tolerant species such as emmer or barley (López-Castañeda & Richards, 1994; Peleg et al., 2005), the dominant taxa in PN, suggest an impoverishment of the growing conditions associated either to less fertile soils or to more drought-prone conditions, or both factors combined. At the same time, drought-sensitive crops, such as flax or pea persisted or even increased, but probably under particular water regimes, e.g. in small irrigated plots or cultivated in river banks, as suggested elsewhere (Araus et al., 1999a; Ferrio et al., 2005).

Table 6
Comparison between age and sex distribution rates among human remains found in the archaeological site of Tell Halula and present values in the Halula region.

Period	Children[a]	Adults				% Children	% Female
		Female	Male	Indet.	Total		
PPNB	47	20	24	17	61	43.5%	45.5%
2004[b]	2.6	2.8	3.0		5.8	31.0%	48.3%

[a] Children below 10 years old.
[b] Average values per household across all communities.

Typical patterns associated to agricultural extensification were also suggested by changes in weed florae. A reduction in weed diversity, together with an increasing presence of cereal-associated weeds, are typically linked to the expansion of cereal-based farming (Aguilera et al., 2008; Bogaard et al., 1999; Jones et al., 2000; José-Maria et al., 2010). At the same time, as agriculture consolidated as the basis of settlement economy, a decline in gathered wild cereals was observed, although some of them, such as *Aegilops*, tended to increase in the archaeobotanical record. This taxon could have been cultivated in late phases of Tell Halula (Buxó and Rovira, in press), although its expansion may also indicate that it was part of the cereal-associated weed florae. Interestingly, the consolidation of a farming society and the progressive abandonment of hunting and gathering are further confirmed from the study of animal remains in Tell Halula (Saña, 1999). Thus, whereas during the M-PPNB wild ungulates still amounted to *ca*. 20% of estimated available livestock biomass, they almost disappeared from animal assemblages during the L-PN (6% of biomass; Saña, 1999).

4.2. Economic expansion and population growth

The archaeological site of Tell Halula is an example of economic expansion in its broader sense, which consolidated the shift from the exploitation of wild resources to a farming economy, already initiated several millennia before (Ferrio et al., 2011). This change had strong consequences in the settlement's economic and social structures, being linked to increasing evidences of a sense of property and the emergence of social classes (Balkan et al., 2008; Molist, 1996; Molist et al., in press). In an initial stage, during the PPNB, the availability of a constant food supply, together with the increasing labour demand of a farming economy, favoured high birth and growth rates, as estimated from the distribution of age classes during this period (Table 6). Nevertheless, growth estimates for PPNB, which considered this effect based on life tables for pre-industrial populations, were comparable to present growth rates in the Halula region, and higher than current average for Syria (2.0%;

C.I.A. 2010). This growth was likely to be kept throughout the PPNB, but in later phases population growth was constrained, and the growth rate at Halula inevitably decreased (Guerrero, 2006). Thus, we found a considerable reduction in site size, in terms of built area and population density, in the PN phase. The settlement shifted from a concentrated nucleus with high density of built structures in PPNB to a more disperse arrangement in PN. This is a general trend observed in the Near East during this period, when large settlements became rare and the number of small sites actually increased (Akkermans and Schwartz, 2003; Molist, 2001). This decrease in population coincided with a decline in grain yield, either due to climate factors or as a consequence of land degradation, and was accompanied by an overall degradation in the quality of domestic built structures (e.g. the substitution of “cimento”-coated soils by beaten soils; Balkan et al., 2008; Molist, 1996). The poor quality of domestic buildings during this period, however, contrasts with the efforts put on collective works (e.g. a village wall, a drainage channel), suggesting that extensification of agriculture was associated to an increase in the hierarchical structure of the society (Balkan et al., 2008; Molist, 1996). Overall, estimates of land requirement per site suggest that population changes may have resulted from an adjustment to keep population size within the capacity of the agroecological system (Table 5). Thus, after a fast growth phase during the PPNB, probably enhanced by more favourable environmental conditions (Ferrio et al., 2011; Riehl, 2008; Willcox et al., 2009), a decrease in yields during the PN resulted in a required land exceeding the available arable land within a manageable distance from the site. Our data suggest that the optimum average cultivated area for the village of Tell Halula was around 160 ha. This is the value obtained during the PPNB phases, but was exceeded by ca. 25% during the E-PN and finally recovered during the L-PN, after a population drop of *ca*. 20%. An optimum cultivation distance from a site has been postulated by Wilkinson (1994), who also proposed that the profitable radius around a site would be proportional to cereal yields, since lower yields would not compensate the extra labour needed for cultivation afar. Consequently, the farmers in Tell Halula would have faced a double constraint during the PN: an increasing demand of arable land due to the lower yields attained, and the unfeasibility to expand cultivated area beyond a certain distance from the site. This situation may lie behind the observed population loss owing to either an increase in mortality (e.g. famine during drought episodes) or farmers’ migration to less exploited areas. Nevertheless, evidence so far do not discard other potential causes, such as political unrest or epidemies, not directly related with food availability.

4.3. Agriculture extensification in present times: what can be learnt from the past?

Present situation in the Halula region is in many aspects comparable to that found in the Neolithic village of Tell Halula. Overall, present data shows a comparable pattern of increased land pressure during a period of fast population growth, which is already causing a progressive impoverishment of life standards, and forcing migration (Arab, 2008). In fact, family incomes tend to derive mainly from off-farm activities (e.g. migrated people, eventual jobs), but this is often not enough to avoid poverty. Land fragmentation appears to be the main problem in the Halula region, with more than 60% of the families being landless, and is the underlying cause for the abandonment of crop rotation and fallow, since in absence of irrigation poor farmers need to use all their land to grow cereals (Arab, 2008). Indeed, although the land actually cultivated per person still fulfil on average the minimum nutritional requirements of the population (Table 5), it may be limiting during low-yielding years. In fact, yields are minimal in about 40% of the years, causing the actual cultivated area to fall below the estimated land requirements in 10 out of the 12 villages studied, and reaching less than 50% of the required land in one third of the communities in such extreme years. If we add to this an unequal distribution of land, we can conclude that available cultivated land is nowadays critical for most families in the Halula region.

In the Neolithic site of Tell Halula, the trend towards a cereal-based farming, regardless of its ultimate causes, also coincided with an increase in inequality and poverty (Balkan et al., 2008; Molist, 1996; Molist et al., in press). Today’s huge achievements in agricultural technology have not modified this trend since resources availability (mainly fertile land and water supply) remain as the main factor limiting productivity of agrosystems in arid environments. Thus no matter whether new crop varieties with greater yield potential and presumably better adaptation to abiotic stresses are deployed, in addition of applying chemical fertilizers, or if mechanization allows to increase the area under cultivation around each community; both economic, environmental and soil-fertility indicators show that population pressure is probably exceeding the productive capacity of agrosystems (Arab, 2008). Although differences in socioeconomic structure and environmental conditions between past and present may eventually bias conclusions, the diachronic comparison of quantitative economic, demographic and environmental information between past and present-time seems to highlight the long-term unsustainability of the interaction between man and environment in the Eastern Mediterranean Basin.

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