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Archaeological
SCIENCE

Analyzing the process of domestication:
Hagoshrim as a case study

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Abstract

Recent excavations at the Neolithic site of Hagoshrim, northern Israel, have yielded a large assemblage of skeletal fragments, representing mostly caprines, cattle and pigs. The three layers of the site's occupation span approximately 2000 years of a crucial period in the domestication of these taxa in the southern Levant, including Pre-Pottery Neolithic C (Layer 6, 7562 ± 85 BP and 7735 ± 55 BP) and the Pottery Neolithic cultures, Jericho IX (Layer 5, 6725 ± 120 BP) and Wadi Raba (Layer 4, 6505 ± 120 BP). Therefore, this site provides an outstanding opportunity to study the process of domestication in a comparative manner, both across taxa and through time. We used kill-off patterns, size reduction and changes in body proportions, and introduced statistical methods to discern the different stages of the domestication process for each taxon. Pig remains reflect simultaneous changes at the end of the 7th millennium BP: kill-off patterns, size and proportions of cranial and post-cranial elements all change between Layer 5 and 4 with no significant changes between Layer 6 and 5. Gradual changes—both between Layer 6 and 5 and between Layer 5 and 4—were found only for cattle, while caprine remains exhibit no changes throughout the site's occupation. These results can be explained in light of the differences between the taxa in terms of their life history strategies, among other things, that can be viewed as pre-adaptations to domestication.
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1. Introduction

The domestication of plants and animals is one of the most influential processes in the development of human civilizations. Numerous studies have focused on understanding the roots and timing of this process as well as its anthropological and evolutionary consequences. Identifying the process of domestication in the archaeozoological record requires the combined use of several criteria, and largely depends on the exact definition of domestication. There is a growing consensus today that domestication should be viewed as a process which includes a continuum of associations between humans and animals, rather than a dichotomy, yet the exact definition and consequently the identifying criteria are still highly debated ([24,38,50,66,83,87]; see also [5,13,34,35, 37,40,56,65] for earlier discussions). We studied the faunal remains of Hagoshrim, a Neolithic site from the southern Levant, in order to gain insight into the different stages of the process of domestication.

A general definition of domestication was given by Ducos [21]: ''Domestication can be said to exist when living animals are integrated to the socioeconomic organization of the human group'' referring, of course, to a population and not to individuals. Ducos [21] further notes that this definition has the advantages of not including apriori assumptions regarding causes, mechanisms and consequences of the process. Yet, being so general it does not provide the theoretical means by which to distinguish different stages of the process. Ducos' definition accords with Zeuner's [88] initial phase of domestication. Zeuner [88] views domestication as an interaction between humans and animals that begins with ''loose ties with the social medium of man'' and ends with ''strict captivity, during which the domesticated beasts cannot have had much opportunity

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of interbreeding with their wild relations", and therefore they are "*wholly* dependent on the social medium of man" (emphasis added). Price [66] also emphasizes the acquisition of adaptations to captive environment as the definitive requisite for domestication. Ervynck et al. [24] define the two end members of the process: "wild" as population not experiencing any direct or indirect influence of human behavior, and "domestic" as a population whose survival, reproduction and nutrition are under complete human control. However, they deliberately refrain from defining intermediate stages.

Two important points arise from the ongoing discussion in the literature. First, domestication in the broad sense may include intermediate stages and manifest in a variety of ways, but domestication in the narrow sense (complete or systematic domestication sensu Zeuner) must include effective reproductive isolation from the wild population. Without isolation, significant behavioral, physiological and morphological changes cannot take place at the population level. This distinction will prove useful when attempting to identify the different stages of the process in the archaeozoological record. Second, while most domesticated species probably go through transitional stages prior to being fully domesticated, in some species these early stages may never lead to domestication sensu strictu (hereby referred to as complete domestication). In these cases the association may take the form of cultural control (best defined in [35]), taming, or semi-domestication, as in the case of elephants, camels and reindeer [59,88]. Defining complete domestication by effective reproductive isolation accords with viewing it as an evolutionary process, as was viewed by Darwin [9,10]. We find that this approach does not exclude the intermediate stages and types of domestication from the discussion (a concern expressed by Ducos [21] and others), but rather helps to elucidate them as what they really are: intermediate [35].

The differences between the various stages and types of domestication lie in the degree to which humans control the animals' survival, reproduction and nutrition. The potential of the animals to breed successfully in captivity is largely determined by the degree to which a species is "pre-adapted" to domestication [26,36,37,66], which contributes to the degree of isolation of the founder population and to the rate and mode of change it experiences. Therefore, any attempt to understand patterns of change that are due to domestication must take into account the animal's unique set of ecological, behavioral and physiological characteristics, as well as its benefits for humans [66,68,70]. With this theoretical framework in mind, we studied the process of domestication of pigs, cattle and caprines in the southern Levant, as revealed in the faunal assemblages of Hagoshrim.

Identifying domestication in the archaeozoological record is usually based upon the combination of several criteria: changes in relative species abundances, changes in demographic parameters such as age distributions and sex ratios, changes in body size and shape, and the appearance of various pathologies. Accepting the distinction between domestication *s.l.* and domestication *s.st.*, as discussed above, it becomes obvious that the different criteria can be considered as indicative of different stages, and that the relative timing of the different changes is as informative as the changes themselves.

Viewing domestication as an evolutionary process, two sources of information are especially useful in shedding light on this process [3,8,65,77,89]: modern experiments in evolution and domestication, and the study of species that dispersed (or were introduced) to islands. These phenomena are characterized by the isolation of a relatively small number of individuals that are transferred to a new environment. The genetic mechanisms influencing those individuals are founder effects, inbreeding and selection, including the relaxation of previous selective forces and the operation of new ones that are determined by the new environment. These mechanisms operate together to accelerate the evolutionary process, which in the case of domestication is further influenced by artificial selection, whether conscious or unconscious.

Based on the paleontological record of deer species in Mediterranean islands, Sondaar [80] found that frequent periods of environmental deterioration resulted in an increase of genetic turnover and selection for smaller individuals. Red deer (*Cervus elaphus*) from Jersey Island reached one-sixth of their initial size in less than 6000 years [52], with no artificial selection involved. Simberloff et al. [77] found a significant size increase in males of Indian mongoose (*Herpestes javanicus*) within 100–200 generations at most (about 50–100 years). Modern experiments show that under strict artificial selection, behavioral and morphological changes can occur within a few generations; e.g. rats (*Rattus rattus*, [48]), musk oxen (*Ovibos monachus*, [84]), asses (*Equus asinus*, [36]) and mink (*Mustela vison*, [51]). Wright [85] conducted inbreeding experiments on *Procavia* and found that the inbred population differentiated from the original population within a few generations, even without selection. Founder effect, the outcome of genetic drift in small and isolated populations, is also expected to cause changes in allele frequency, that is, evolutionary changes, within several generations [3,65,71]. Therefore, morphometric changes can be expected to occur fairly quickly, once effective isolation is maintained, and, by definition, can serve as the best indication for complete domestication. Yet, they say very little about the process preceding isolation.

An increase in abundance of pathologies, an initial increase of phenotypic variation followed by a decrease, and a high infant mortality are also possible outcomes of the founder effect and inbreeding [3,48,65,67,88]. Yet, these phenomena can occur also in earlier stages, i.e. without effective isolation, due to stress in confined

animals [36,65] as well as to different management strategies and selective capture [34,50,56,58,81,82,87]. Therefore, changes in demographic parameters and body size can be considered indicative of some change in the association between humans and the species in question, but not necessarily of complete domestication. Changes in relative abundances of a certain species can be considered the earliest sign for the beginning of the domestication process, given that the same species is known to be domesticated at later times.

Thus, identifying domestication in the archaeozoological record requires the combination of various criteria, not only because none is decisive enough, but also because domestication is a process and not a dichotomy. Different stages are expected to appear differently in the record, and species that differ in their ecological, behavioral and physiological characteristics, as well as in their exploitation by humans, are expected to go through the process in a different manner.

For this study we examined the remains of the three earliest economically valuable domesticated taxa from the southern Levant: caprines (*Capra* and *Ovis*), cattle (*Bos*) and pigs (*Sus*). We developed a statistical framework that enabled us to study the process of domestication in a comparative manner, both through time and across taxa, based on kill-off patterns, body size changes and changes in body proportions. As these criteria are considered to represent different stages of the process, the patterns found for the different taxa should enable us, on one hand, to evaluate our methods, and on the other hand, to gain insight into the process of domestication of these taxa. The timing and mode of changes found for each of the three taxa will be compared and discussed in view of their specific attributes and their regional archaeozoological record.

2. The site and the chronological context

Hagoshrim, a prehistoric site in the Hula valley, northern Israel, was excavated as a salvage excavation by Nimrod Getzov of the Israel Antiquities Authority. Two seasons of excavation—1996 and 1997—revealed a large site of about 80,000 m^2 of which 1600 m^2 was recovered. Three main strata were identified [27]: Layer 6 (7562 ± 85; 7735 ± 55 BP), a Pre-Pottery Neolithic C culture; Layer 5 (6725 ± 120 BP), a Pottery Neolithic B culture equivalent to Jericho IX; and Layer 4 (6505 ± 120 BP), associated with the Wadi Raba culture. The faunal assemblages are relatively large and well preserved and the main layers are laterally displaced, so that overlap is minimal and the chronological context is clearly defined. This is especially critical for the PPNC, since this is a relatively new archaeological entity (e.g. [1,25,28,72]) (Table 1).

It is widely accepted that the main stages of the "Agricultural Revolution" in the Levant took place

Table 1
The three main layers of Hagoshrim, their chronological and cultural context and the uncalibrated radiocarbon dates obtained for each layer

Layer 6	Pre-Pottery Neolithic C		7562 ± 85 BP
			7735 ± 55 BP
Layer 5	Pottery Neolithic B	Jericho IX	6725 ± 120 BP
Layer 4	Late Neolithic/ Early Chalcolithic	Wadi Raba	6505 ± 120 BP

during the Neolithic period. Goat domestication is clearly evident by both morphometric and demographic parameters by the PPNC [20,45,64,83,87]. Sheep were most likely domesticated in the northern Levant during the 10th millennium BP [64] and introduced to the southern Levant by the end of the 9th millennium BP, that is, the mid-PPNB [20,22,41,44,83]). The earliest evidence for size reduction of cattle is from the northern Levant and is assigned to the mid-PPNB [65]. Based on evidence from the southern Levant it is very likely that cattle domestication began at the end of the Pre-Pottery Neolithic [11,34,45]. Domestic pigs have been clearly identified so far only in the Wadi Raba culture [16,39,45], that is by the end of the Pottery Neolithic. Thus, the stratigraphy of Hagoshrim spans a critical period for the study of animal domestication in the southern Levant and provides a unique opportunity to carry out a diachronic study.

3. Material and methods

The material was recovered using a 2 × 2 mm mesh. Only a small sample of each layer was wet sieved. Evidence such as cut marks, gnawing and burning is rare. Dark clay covered most of the fragments, but was easily removed. The use of acetic acid for cleaning of the bones was not necessary. A total of 7757 skeletal fragments were identified to either genus or species level (Fig. 1), using the comparative collections curated at the Tel-Aviv University Zoological Museum, and at the Department of Evolution, Systematics and Ecology in the Hebrew University of Jerusalem. All calculations are based on NISP. This is justified mainly since most of the material was found on living floors, throughout the site, and apparently the inhabitants used to accumulate animal remains in waste pits and then reused and incorporated them in the floors (Getzov N., pers. com.). Such a scenario is expected to increase independence among the fragments, and indeed, articulated bones were very rare. All statistical analyses were done with STATISTICA^{TM}.

Sheep and goat remains were clumped together for want of a reliable method to distinguish a sufficient number of elements. Based on Boessneck [4] and Payne [60], distal humeri, astragali and distal metapodials were separated to species to a certain degree, but the samples retrieved were too small for the morphometric analyses (Haber, unpublished data). The criteria suggested by
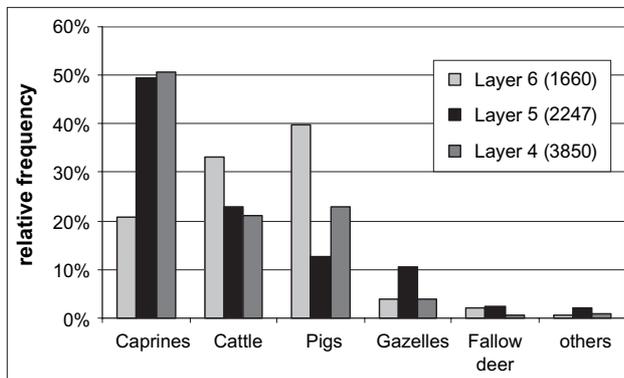
Fig. 1. Species composition of the three layers. "others" include species of relative abundance less than 2%. Numbers in parentheses are sample sizes (NISP).

Boessneck [4] for other elements were either found insufficient or irrelevant in the case of Hagoshrim. Therefore, results for caprines may include a certain bias. However, the ratio of sheep to goats based on distal humeri, astragali and distal metapodials, is statistically consistent throughout the layers, thus reducing potential bias (Haber, unpublished data).

3.1. Kill-off patterns

Five age groups were defined based on both loose teeth and tooth rows, since complete tooth rows were rare (Tables 2−4). Eruption and wear stages were recorded based on Payne [61,62], Deniz and Payne [18] and Grant [29] for sheep and goats (Table 2); Grant [29] for cattle (Table 3); and Grant [29] and Bull and Payne [6] for pigs (Table 4). In order to coordinate between wear stages of different teeth, absolute ages were used based on data reported in Davis [15], Payne [61,62] and Silver [76] for sheep and goats; Silver [76] for cattle; and Bull and Payne [6] and Silver [76] for pigs. We used

a collection of 21 adult pigs, males and females, curated in the Zoological Museum of Tel-Aviv University, for the construction of age groups for pigs, enabling the use of both upper and lower dentition. The differences between eruption and wear of lower and upper teeth, reported for pigs by Matschke [53] and Bull and Payne [6] proved negligible. This is mainly due to the relatively low resolution defined for this study (5 age groups). A lower resolution results also in a bigger sample for each group, thus reducing the impact of random effects.

The use of isolated teeth involves a unique complication, rarely addressed in the archaeozoological literature. As can be seen in Tables 2−4, some age groups are represented by more elements than others, and are thus prone to be artificially over-represented. In order to avoid this bias when interpreting the final age distributions, a two-dimensional (age groups over layers) X^2 test was applied [79]. In this case, the expected value for each cell (a specific age group in a specific assemblage/layer) was calculated based on an intrinsic hypothesis, that is, based on the total relative abundance of that age group (ratios of rows) and the total relative abundance of layers (ratios of columns), so that the relative differences are considered, rather than the absolute. The analysis yields values of standardized deviates, calculated as the square root of the X^2 value of each cell, from which the relative deviation of each cell can be easily read in terms of both degree and direction. Note that the X^2 statistic is similar but not identical to the χ^2 distribution. The X^2 statistic is based on discrete values while the χ^2 distribution is based on continuous values, but it does result in an approximation to the continuous distribution so the χ^2 distribution can be used for the significance test. A necessary and unavoidable assumption is the independence of the fragments, as is always the case when using NISP rather than MNI. Tooth rows were each counted only once, based on one of the teeth preserved.

Table 2
The five age groups used for caprines and their definitions, based on eruption and wear of dP/4, P/4 and M/3 (lower only)

		Age group with absolute ages in months				
		AG-1: (A−C) 0−12	AG-2: (D) 13−24	AG-3: (E) 25−36	AG-4: (F) 37−48	AG-5: (G−I) over 48
Element	dP/4	a−h all cusps in wear with enamel inside	j−n no enamel inside the first (anterior) cusp			
	P/4		a-(b or c) dentin of posterior (small) cusp invisible	(c or d)-f dentin of posterior cusp exposed but not connected	g−h all dentin exposed and connected	j−k no enamel inside both cusps
	M/3		a no dentin exposed. Root is open	b−d dentin of the two anterior cusps exposed	e-(f or g) dentin of third cusp exposed but not connected on the lingual side	(g or h)-m all dentin exposed and connected

Small letters in each cell correspond to Grant's [29] stages. Capital letters in parentheses correspond to Payne's [61] stages.

Table 3
The five age groups used for cattle and their definitions based on eruption and wear of dP/4, P/4 and M/3 (lower teeth only)

		Age group with absolute ages in months				
		AG-1: 0–12	AG-2: 13–24	AG-3: 25–36	AG-4: over 36	AG-5: senile
Element	dP/4	a–g dentin of cusps exposed and connected	h–m appendages between cusps are in wear			
	P/4			a–c buccal dentin exposed	d–h lingual dentin exposed and connected	j no enamel within cusp
	M/3			a–d dentin of third (posterior) cusp invisible	e–j dentin of third cusp exposed, dentin of appendage exposed but not connected	h–m dentin of appendage exposed and connected

Small letters in each cell correspond to Grant's [29] stages.

3.2. Morphometric analyses

Measurements were taken from various elements following von den Driesch [19] and Davis [13]. Only fully ossified and unburned fragments were measured. The Log-Ratio technique was used to facilitate comparisons between different elements. This method was first developed by Simpson et al. [78] and was later modified and widely employed by archaeozoologists under the name of "difference of logs" or "log-size index" (e.g. [34,38,55,63]). Basically, a size index is calculated by carrying a logarithmic transformation of the ratio between a specific measurement and a standard. This method provides graphic means by which to compare measurements from different skeletal elements, scaling all measurements to a common reference.

As was noted by previous researches (reviewed in [57]), the Log-Ratio technique cannot by itself be used to enlarge sample size, unless it is shown that the body proportions of the studied populations do not differ significantly from those of the standard values. In other words, if we were to test the differences between the three layers of Hagoshrim by pooling together measurements from different elements, for the sake of larger samples, we may be violating the assumption of homogeneity of variance, required in a one-way ANOVA [79]. However, by using a two-way ANOVA (elements over assemblages or layers), we test for this assumption at the same time as we test for the overall size changes, thus addressing the question of both size and shape, while using the whole sample. The issue of sample size is avoided because it is the total number of measurements that is crucial, as well as the number of cells, rather than the number of measurements in each cell [79], as long as each cell includes at least two measurements.

It is important to note that the logarithmic transformation is essential for the ANOVA since it tends to normalize skewed distributions (as opposed to other size indices such as the ones proposed in [23,24]). Although calculating the ratios between measurements is enough

Table 4
The five age groups used for pigs and their definitions based on eruption and wear of upper (\) and lower (/) dP3, dP4, P4 and M3

		Age group with absolute ages in months				
		AG-1: 0–6	AG-2: 7–18	AG-3: 19–24	AG-4: 25–36	AG-5: older
Element	dP/3	Dentin invisible	Dentin exposed			
	dP\3	Dentin invisible	Dentin exposed			
	dP/4	a–d dentin invisible	e–j dentin exposed			
	dP\4	Dentin invisible	Dentin exposed			
	P/4		a–c dentin invisible	d–e dentine exposed, but patchy	f one patch of dentin, cusp still high	g–h low cusp
	P\4		a–c dentin invisible	d–e dentine exposed, but patchy	f lingual patch of dentin appears, cusp still high	g–h low cusp
	M/3			a root still open	b–c dentin invisible or little patches and last cusp unerupted	d–k big patches of dentine
	M\3			Root still open	Dentin invisible and last cusp unerupted	Big patches of dentine

The small letters in each cell correspond to Grant's [29] stages.

to put them on the same scale, ratios are inappropriate for parametric analyses without an appropriate transformation. The transformation commonly used to normalize ratios is the arc-sinus transformation [79], but the logarithmic one should work as well [47]. To be on the safe side, the data were tested for normality. Since the database is arranged as a two-way table, with both elements and layers as independent grouping factors, each cell (specific element in a specific layer) should be tested for normality rather than the combined database. However, the number of measurements in each cell is too small to discern any true distribution. To overcome this problem standardization procedure is usually recommended [79] and was employed in this study, as a preceding analysis, for the purpose of testing for normality. The data from each cell were standardized using the following equation: $(Y - Y_{avg})/SD$, where Y is a measurement, Y_{avg} and SD are the average and the standard deviation, respectively, of the specific cell. Once all the measurements are standardized in this manner, a normality test was carried out for the combined database.

As the reference values for the LSI transformation of caprines we used measurements published by Davis [14] for female sheep. For cattle we followed Grigson [34] and used the measurements of a female aurochs from the 16th century AD, published by Degerbøl and Fredskild [17]. For pigs we used measurements of a female Anatolian boar published by Hongo and Meadow [38] for the post-cranial remains and used data from Mayer et al. [54] for the upper and lower third molars. It is important to remember, however, that the comparisons are among the fossil assemblages and not between them and the standard, which only serves as a common reference point. The tooth measurements are compared to data from Nahal Zehora [16] that come from two layers, Yarmukian (chronologically between PPNC and Jericho IX) and Wadi Raba. The site is located close enough to Hagoshrim to be geographically comparable.

4. Results

As in many other Neolithic sites in the southern Levant, the economy of Hagoshrim is based on four main species (Fig. 1): cattle, sheep, goats and pigs. Pigs comprise 40% of the faunal remains in Layer 6 and 22% in Layer 4. Caprines predominate in the pottery Neolithic, Layers 5 and 4.

4.1. Kill-off patterns

The distributions of age groups are summarized in Tables 5, 6 and 7 for caprines, cattle and pigs, respectively. The sums of the columns give the total

Table 5
Caprine mandibular teeth assigned to age groups

		AG-1: (A–C) 0–12 m	AG-2: (D) 13–24 m[a]	AG-3: (E) 25–36 m	AG-4: (F) 37–48 m	AG-5: (G–I) over 48 m	Total
Layer 6	dP/4	4					4
	P/4		1	1	4	4	10
	M/3		4	2	3	2	11
	Total	**4**	**5**	**3**	**7**	**6**	**25**
Layer 5	dP/4	16	20				36
	P/4		10	17	25	3	55
	M/3		12	12	17	40	81
	Total	**16**	**42**	**29**	**42**	**43**	**172**
Layer 4	dP/4	34	30				64
	P/4		21	21	27	15	84
	M/3		17	23	40	54	134
	Total	**34**	**68**	**44**	**67**	**69**	**282**

Totals (in bold font) give the kill-off pattern for each of the three layers.
  [a] The prime age, based on eruption of M/3.

distributions, or kill-off patterns. The standardized deviates—which are the square root of the X^2 value of each cell—are given in Figs. 2, 3 and 4, for caprines, cattle and pigs, respectively. Due to the small samples, the expected distribution for cattle yielded values that are smaller than 5 for several cells and therefore the youngest two age groups (AG-1 and AG-2) and the oldest two age groups (AG-4 and AG-5) had to be combined [79]. The important thing, however, is that prime age is still discernable from this table.

Both caprines (Fig. 2) and cattle (Fig. 3) yielded no significant changes in kill-off patterns among the layers. For caprines the SDs ranged between ± 0.8, $p = 0.98$, and for cattle the SDs were ± 1.3, $p = 0.27$. The apparent difference in Layer 5, for both caprines and cattle, is not significant. For pigs, on the other hand, there is a significant difference between the layers,

Table 6
Cattle mandibular teeth assigned to age groups

		AG-1: 0–12m	AG-2: 13–24m	AG-3: 25–36m[a]	AG-4: over 36m	AG-5: senile	Total
Layer 6	dP/4	0	2				2
	P/4			4	3	0	7
	M/3			3	5	0	8
	Total	**0**	**2**	**7**	**8**	**0**	**17**
Layer 5	dP/4	6	5				11
	P/4			1	3		4
	M/3			4	3	6	13
	Total	**6**	**5**	**5**	**6**	**6**	**28**
Layer 4	dP/4	8	5				13
	P/4			5	3		8
	M/3			10	14	1	25
	Total	**8**	**5**	**15**	**17**	**1**	**46**

Total (in bold font) give the kill-off pattern for each of the three layers.
  [a] The prime age, based on eruption of M/3.

Table 7
Pig mandibular (/) and maxillary (\) teeth assigned to age groups

		AG-1: 0–6m	AG-2: 7–18m	AG-3: 19–24m[a]	AG-4: 25–36m	AG-5: older	Total
Layer 6	dP/3	0	1				1
	dP\3	0	1				1
	dP/4	0	6				6
	dP\4	0	2				2
	P/4		0	6	4	0	10
	P\4		3	2	2	1	8
	M/3			1	7	4	12
	M\3			4	4	2	10
	Total	**0**	**13**	**13**	**17**	**7**	**50**
Layer 5	dP/3	0	5				5
	dP\3	1	6				7
	dP/4	0	4				4
	dP\4	0	0				0
	P/4		1	6	3	0	10
	P\4		2	4	3	0	9
	M/3			6	4	5	15
	M\3			3	2	3	8
	Total	**1**	**18**	**19**	**12**	**8**	**58**
Layer 4	dP/3	7	15				22
	dP\3	3	13				16
	dP/4	18	31				49
	dP\4	4	24				28
	P/4		2	16	7	1	26
	P\4		5	19	14	5	43
	M/3			13	16	9	38
	M\3			12	17	10	39
	Total	**32**	**90**	**60**	**54**	**25**	**261**

Totals (in bold font) give the kill-off pattern for each of the three layers.

[a] The prime age, based on eruption of M/3.

$p = 0.02$, with SDs $\pm$ 2.2. The main change is between Layer 5 and 4 with a clear pattern of younger culling age with time. It is important to remember that these results are purely relative, since they are based on an intrinsic hypothesis. Therefore, any attempt to combine them with results from other assemblages will require re-analyzing the raw data from all the assemblages in question.

4.2. Morphometrics

Normality tests yielded no significant difference between the standardized LSI values and a normal distribution for any of the three taxa. Kolmogorov–Smirnov test yielded $p > 0.2$ for all three taxa, and Shapiro–Wilk yielded $p = 0.154$, $p = 0.076$ and $p = 0.575$, for caprines, cattle and pigs, respectively. No outliers were detected. Tables 8, 9 and 10 present the ANOVA results for caprines, cattle and pigs, respectively. Summary statistics of the measurements are given in Appendices A–C. Raw data will be published with the site report (Haber et al., in prep.).

For caprines, there is no significant difference between the layers, neither 6 to 5 nor 5 to 4, which means
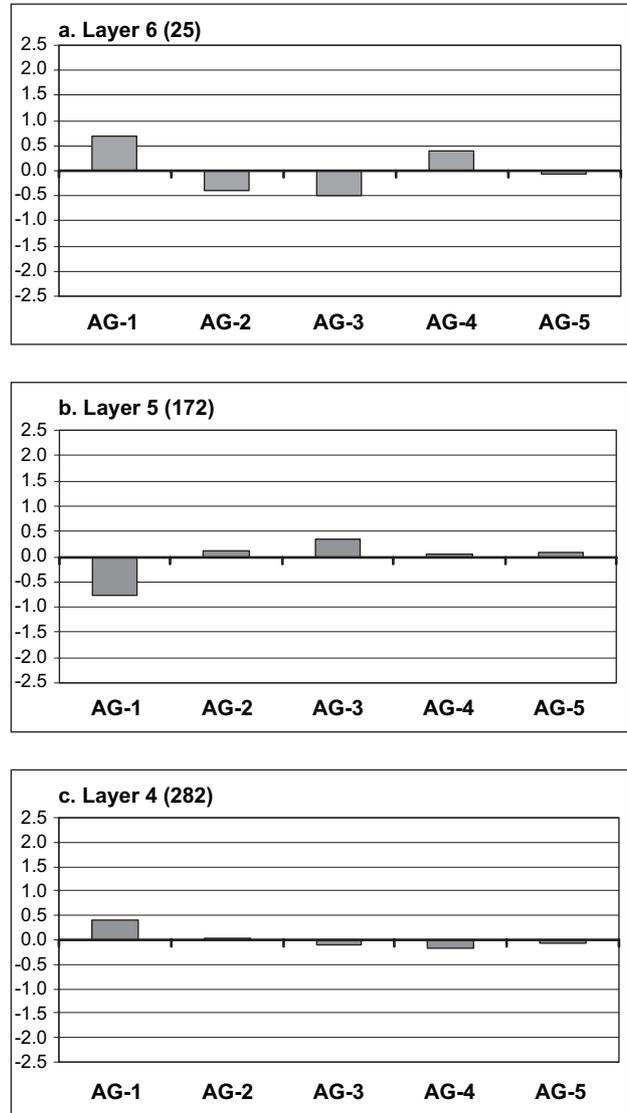

Fig. 2. Caprines. Standardized deviates of the age groups in each layer, assuming independence between age groups and layers. Numbers in parentheses are sample sizes. $X^2 = 2.0283$, df = 8, $p = 0.98$. Data from Table 5.

that there is no over-all size change (Table 8). The difference between the elements means that different elements from the fossil assemblages differ in their deviation from the standard, but this deviation from the standard is consistent throughout the layers since there is no interaction between layers and elements. Therefore, the fossil assemblages differ in their body proportions from the standard, which is not surprising and only reinforces the importance of comparing several elements simultaneously, but they do not differ among themselves.

The same analysis for cattle yielded a different pattern (Table 9). Both the layers and the elements differ significantly among themselves, for both Layer 6 vs. Layer 5 and Layer 5 vs. Layer 4, but there is no significant
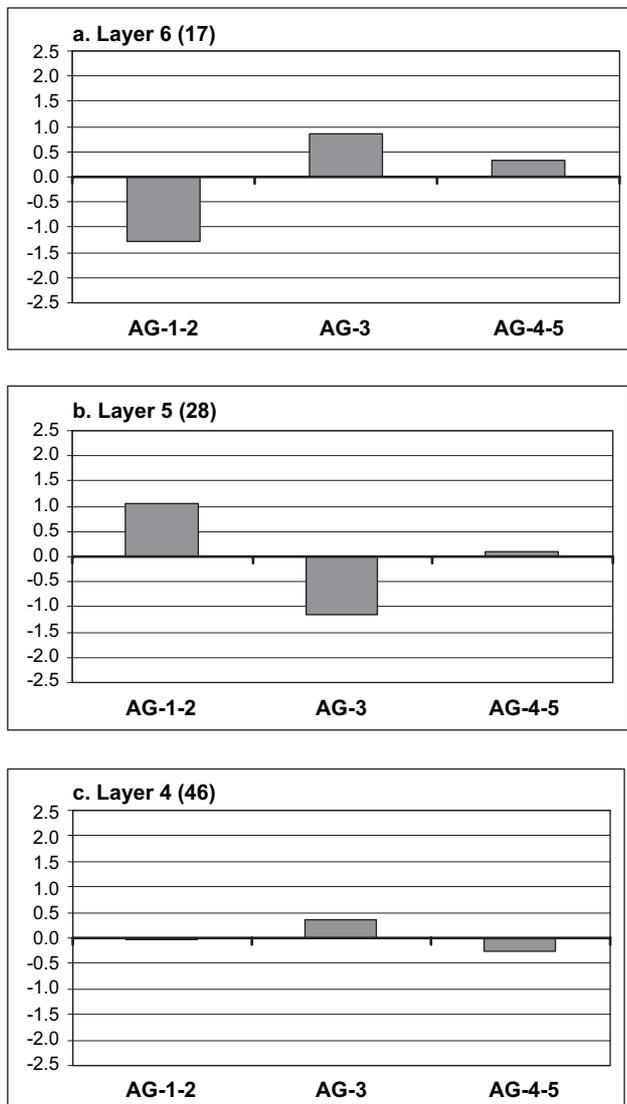
Fig. 3. Cattle. Standardized deviates of the age groups in each layer, assuming independence between age groups and layers. Numbers in parentheses are sample sizes. $X^2 = 5.215$, df $= 4$, $p = 0.27$. Data from Table 6.
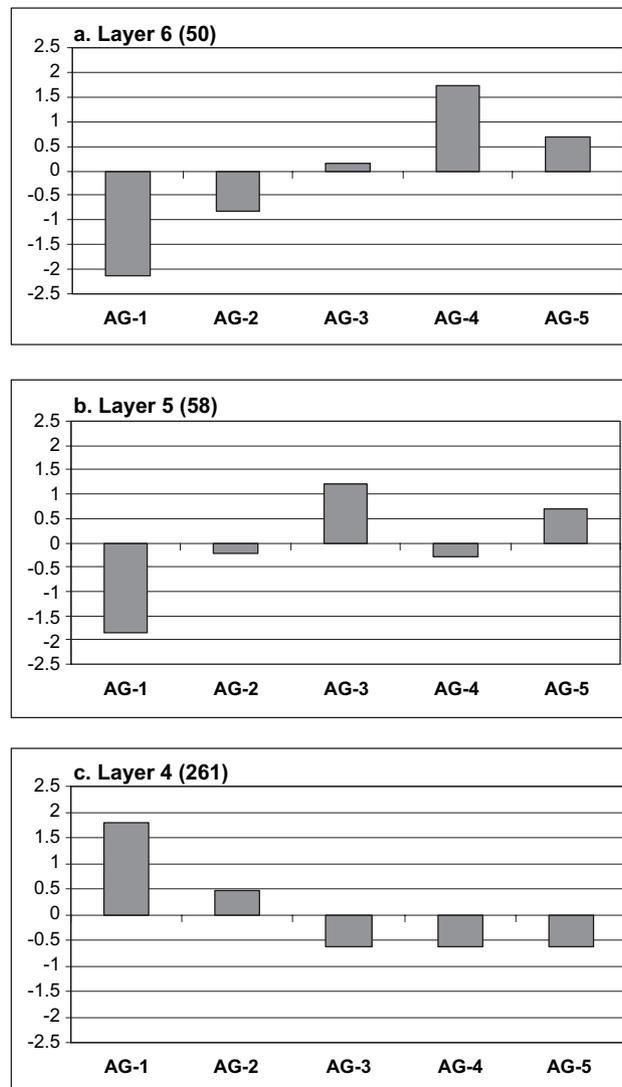

Fig. 4. Pigs. Standardized deviates of the age groups in each layer, assuming independence between age groups and layers. Numbers in parentheses are sample sizes. $X^2 = 18.607$, df $= 8$, $p = 0.02$. Data from Table 7.

interaction. Therefore, an overall change in size is indicated, but no change in proportion through time. For pigs, on the other hand, there is a significant change in both proportions and body size between Layers 5 and 4, but no change at all between Layers 6 and 5 (Table 10).

These patterns can be seen clearly when the averaged LSI values are plotted against the standard (Fig. 5). If the fossil assemblages have the same body proportions as the standard they should yield a line that is parallel to the x-axis, whether below it (for smaller body size) or above (for larger body size). If they have similar proportions among themselves then they should exhibit a similar curve, whatever its shape. Consistent with the statistical results, the caprines have almost identical curves for the three layers (Fig. 5a), cattle have three

curves of similar shape although of gradually lower values, and pigs have identical curves for Layers 6 and 5 and a completely different one for Layer 4 as well as lower values.

Further insight into the status of pig remains is provided by studying the morphological proportions of their dentition, taken to represent skull shape. A positive slope in Fig. 6 indicates a relative shortening of the teeth. Based on tooth width, it appears that the remains from Layer 6, and from the Yarmukian of Nahal Zehora (from [16]), are smaller than those of recent wild pigs. Yet, when we examine width relative to length we can see that the difference is actually in the proportions of the fossil assemblages relative to the recent material. This implies that these Neolithic populations are

Table 8
Two-way ANOVA for LSI values of caprines

	df effect	MS effect	df error	MS error	F	p-level
(a) Layer 6 vs. Layer 5						
Measurements included: As-GL; Hu-BT; Hu-HTC; MC-BFd; MT-BFd; Ra-Bp; Sc-GLP; Sc-SLC; Ti-Bd						
Layer	1	0.00523	149	0.00165	3.16719	0.08
Element	8	0.00408	149	0.00165	2.46975	**0.02**
Interaction	8	0.00152	149	0.00165	0.91763	0.5
(b) Layer 5 vs. Layer 4						
Measurements included: As-GL; Ca-GL; Hu-BT; Hu-HTC; MC-BFd; MC-BFp; Ra-Bp; Sc-GLP; Sc-SLC; Ti-Bd; MT-BFd						
Layer	1	0.00304	408	0.00134	2.26341	0.13
Element	10	0.00857	408	0.00134	6.38159	**<0.00001**
Interaction	10	0.00232	408	0.00134	1.72725	0.07

Only one measurement was included from each fragment. The measurements and the abbreviations follow von den Driesch [19] and Davis [13].

probably wild, and they differ from the recent material by having a somewhat longer rostrum. In Layer 5 we can already see size reduction, but no shortening of the teeth. Both Layer 4 and Wadi Raba of Nahal Zehora already show a shortening of the teeth relative to earlier populations, although they are not as short as those of recent feral pigs (from [54]).

5. Discussion

By combining different criteria and subjecting the data to the appropriate statistical testing we were able to follow through the process of domestication, and to gain insight into the differences between the taxa. Our results suggest that the three earliest economically valuable taxa in the Levant differ in the timing and mode of change involved with their domestication. As discussed below, these differences may be related to differences in their biological characters, as well as their utilization by humans.

No significant changes were found in either kill-off patterns or morphometric characters of caprines throughout the site's occupation, indicating continuous herd management strategies and further corroborating the prevalent understanding that complete domestication of sheep and goats, in the narrow sense of having

effective isolation from the wild, was accomplished by the PPNC [20,22,41,44,45,64,83,87]. The similarities between Layers 6 and 4 are especially instructive in this context. This allows us to use their remains as a "control", to which the results of cattle and pigs can be compared, providing support for the reliability of our methods. The constancy of these patterns also agrees with previous suggestions [12,31,75] that systematic utilization of secondary products did not occur prior to the 6th millennium BP.

The cattle of Hagoshrim show no significant changes in kill-off patterns, indicating continuous herd management strategies throughout the site's occupation. However, a trajectory of continued size reduction, although with no change in body proportions, is also indicated. It is important to note that cattle are characterized by pronounced sexual size dimorphism that impedes the interpretations. It is reasonable to expect that size reduction at the population level would be reflected in shifting of the whole range while a change of sex ratio would result in merely shifting of the mean or the median [21,49,56,64]. Yet, the greater the natural variation in the population, the higher the chance that both the average size and the range would shift as a result of change in sex ratio and not due to size change in the population level, especially when the samples are not big.

Table 9
Two-way ANOVA for LSI values of cattle

	df effect	MS effect	df error	MS error	F	p-level
(a) Layer 6 vs. Layer 5						
Measurements included: As-GL; Hu-BT; MC-BFp; MT-BFp; PH1-Bp; PH2-Bp						
Layer	1	0.00795	125	0.00171	4.64872	**0.03**
Element	5	0.00412	125	0.00171	2.41228	**0.04**
Interaction	5	0.00240	125	0.00171	1.40170	0.23
(b) Layer 5 vs. Layer 4						
Measurements included: As-GL; Hu-BT; MC-BFd; MC-BFp; MT-BFd; MT-BFp; M/3-GL; PH1-Bp; PH2-Bp; Ti-Bd						
Layer	1	0.03407	240	0.00158	21.60601	**<0.00001**
Element	9	0.00931	240	0.00158	5.90290	**<0.00001**
Interaction	9	0.00152	240	0.00158	0.96710	0.47

Only one measurement was included from each fragment. The measurements and the abbreviations follow von den Driesch [19] and Davis [13].

Table 10
Two-way ANOVA for LSI values of pigs

	df effect	MS effect	df error	MS error	F	p-level
(a) Layer 6 vs. Layer 5						
Measurements included: As-GL; MC3-Bp; Ra-BFp; Sc-GLP; Ti-Bd; Ul-BPC						
Layer	1	0.00012	72	0.002179	0.05505	0.82
Element	5	0.009402	72	0.002179	4.315395	**0.002**
Interaction	5	0.00241	72	0.002179	1.105965	0.36
(b) Layer 5 vs. Layer 4						
Measurements included: As-GL; MC3-Bp; MT3-Bp; Ra-BFp; Sc-GLP; Ti-Bd; Ul-BPC						
Layer	1	0.067543	147	0.001961	34.44127	**<0.00001**
Element	6	0.00713	147	0.001961	3.63588	**0.002**
Interaction	6	0.004471	147	0.001961	2.279833	**0.04**

Only one measurement was included from each fragment. The measurements and the abbreviations follow von den Driesch [19] and Davis [13].

The kill-off patterns of pigs indicate some change through time, with a clear pattern of younger culling age, particularly at the end of the Pottery Neolithic between Layers 5 and 4. This change is accompanied by a simultaneous change of both size and shape. It is therefore safe to conclude that the remains of Layer 6

represent wild boars, while Layer 4 represents a fully domesticated population. Understanding the process that precedes these changes, however, is less obvious.

Modern experiments and studies of species dispersal to islands indicate that morphometric changes can be expected to occur fairly quickly once effective isolation between the domesticated and wild population is achieved. The degree to which an animal is "pre-adapted" to domestication in a specific region determines its ability to reproduce in captivity, so that need to repeatedly trap wild animals is reduced, and isolation is more effective. Therefore, theoretically, species that are better "pre-adapted" to domestication in a specific region, can be expected to show morphometric changes relatively soon after the first sign for a change in their association with humans, i.e. drastic change in relative abundance. On the other hand, species that are less "pre-adapted" to domestication can be expected to go through a relatively prolonged phase of cultural control prior to the establishment of effective isolation, indicated by demographic changes and perhaps size reduction occurring earlier than changes in shape.

Pre-adaptations to domestication and their implications were discussed thoroughly by Herre and Rohrs [37] and Garrard [26]. Hecker [35] emphasized the importance of the environment in determining the potential for different types of associations between humans and
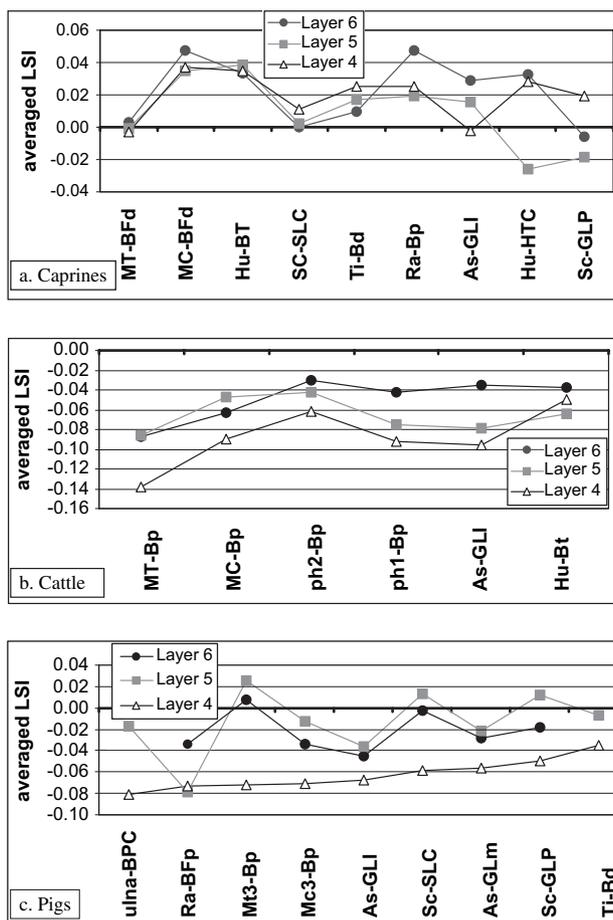
Fig. 5. Averaged LSI of various measurements of (a) caprines (b) cattle and (c) pigs. *x*-axis represents the reference values. As, astragalus; Ca, calcaneum; Hu, humerus; MC, metacarpal; MT, metatarsal; MC3, 3rd metacarpal; MT3, 3rd metatarsal; Ph1, 1st phalanges; Ph2, 2nd phalanges; Ra, radius; Sc, scapula; Ti, tibia; Ul, ulna.

Fig. 6. Mean LSI values of length (*L*) and width of anterior cusp (WA) of the upper and lower 3rd molar of pigs from various assemblages. Numbers in parentheses are sample sizes (NISP). NZ, Nahal Zehora (from [16]); data for feral are from [54].

animals, while Hemmer [36] explored the role of social and psychological attributes. Assuming that early domesticates were used as meat suppliers, palatability, high yield of nutritional value and high reproductive rate are important characteristics. Physical and mental endur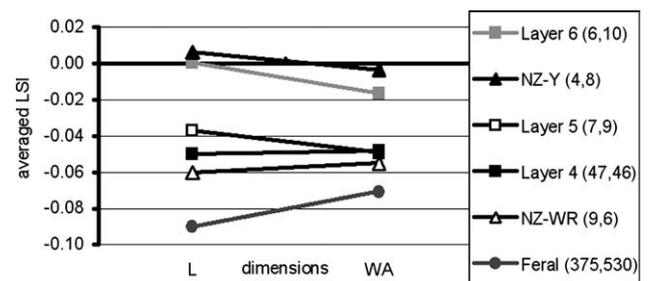ance increase the chances that the founder herd will survive the transfer from its natural environment and will be easily integrated into the human environment. The ability to exploit a wide range of habitats and food types contributes to the ability of the herd to survive difficult times. Social animals are less sensitive to crowded conditions and psychological stress. They accept human dominance more easily, as part of their natural hierarchical structure. Polygamy allows keeping only few males for a big herd of females, which helps controlling the herd but also assists in artificial selection.

Cases such as the reindeer and elephants are especially instructive in this context, as these animals are exploited by humans for their unique adaptations to extreme environments, rendering morphological changes undesired [88]. Moreover, their ecological and behavioral characteristics, e.g., the enormous amounts of food required to feed elephants, reduce the net gain of keeping domestic individuals. Indeed, neither reindeer nor elephants have been fully domesticated, and are constantly bred with wild animals.

Based on the above considerations, it can be seen that the progenitors of sheep and goats can be considered the ideal species for early domestication, especially in relatively arid environments. Goats became a dominant species in the economy of the Levant by the mid-PPNB, and by the PPNC—about 500 years later—their domestication is clearly evident by both morphometric and demographic parameters [20,45,64,87]. The goats of Ain Ghazal were recently shown to be domesticated *s.st.* already by the mid-PPNB [83]. Autochthonous domestication was identified also in the Zagros region [87] and perhaps also in southeastern Turkey [64], again with less than a 1000 years between a drastic increase in relative abundance and clear changes in size and shape. Sheep were most likely domesticated in the northern Levant during the 10th millennium BP [64], where changes in kill-off patterns, size and shape can be traced locally through time. Lack of intermediate stages and assumptions regarding their original distribution have led to the conclusion that sheep were introduced to the southern Levant as fully domesticated by the end of the 9th millennium BP, that is, the mid- to late-PPNB [20,22,41,44,83]. Therefore, from the data accumulated so far it seems that effective isolation was achieved within less than 1000 years, and perhaps even less than 500 years, since the first sign of change in their contribution to meat consumption. This is quite certainly true for goats, and probably also for sheep. Thus, the constancy found in Hagoshrim is in accord with data from previous studies, as well as the patterns expected from theoretical considerations of caprine characteristics.

The record of cattle and pigs is more problematic, mainly because samples are usually too small for thorough analysis. Cattle are the first large animals to be domesticated and are more difficult to manage and herd. Therefore it is reasonable to assume that the various factors affecting size reduction, e.g. artificial selection, physiological and psychological stress, would be more pronounced. Moreover, cattle have a narrower range of tolerance for food and water supply, rendering it more difficult to maintain their needs in confinement. Cattle become the 2nd or 3rd most abundant species in the Levant approximately in the mid-PPNB [45,64]. Demographic patterns are usually difficult to reconstruct although there is some tendency towards high frequencies of adults in the earlier sites [20,41,45,46]. The earliest evidence for domestication of cattle, based on size reduction, comes from the northern Levant and is assigned to the mid-PPNB [64]. These remains also indicate an increase in frequencies of females and juveniles. Davis [11] and Grigson [34] compiled data from various sites around the Levant encompassing the PPNA through the Chalcolithic, and both concluded independently that size reduction of cattle, that can be associated with domestication, began in the southern Levant at the end of the PPN. Their data also suggest that this trend continued at least into the Chalcolithic. Thus, as was found for caprines, the patterns found for cattle in Hagoshrim are in accord with data from previous studies, as well as the patterns expected from theoretical considerations. More specifically, the consistent kill-off patterns, especially the similarity between Layer 6 and 4, and the gradual size reduction, support the idea that cattle domestication was well under way before the end of the PPN. At the same time, the fact that size reduction continued for a prolonged period of time, and that no changes in body proportions occurred throughout the PN, suggests that effective reproductive isolation was not maintained as easily as for caprines.

From various aspects, pigs resemble dogs and humans more closely than caprines and cattle [8,26]. As omnivores, pigs can feed on a wide variety of food [8,30,33,59,73,86], including bones [30], so they can be fed easily with leftovers, while helping to eliminate rotten food from the settlement. In addition, their reproductive abilities and fat content are higher and traditionally their utilization by humans has been limited to their meat and fat. However, the range of temperatures and humidity they endure is narrower and in arid environments they are more likely to compete with humans and to cause damage to crops, rather than serve as a useful resource. This is probably one of the main reasons why pigs have been so favored by early European herders [2,33], while in Egypt pigs have been conceived as representing everything that is evil, and were partially banned, at least since the Middle Kingdom ([8], Haris 1985 in [86], and [69]), and are

considered less pre-adapted for domestication [8,26]. Indeed, ethnographic studies indicate a wide variety of interactions between pigs and humans, wider than that found for caprines and cattle, differing in the extent of control humans have over their breeding, feeding and survival [32,33,70,74]. These characteristic and ethnographic studies render it highly probable that pigs have gone through the process of domestication differently than did other early domesticates of the Middle East, i.e. sheep, goats and cattle [68,70].

High frequencies of pigs first appear in the southern Levant by the end of the Pre-Pottery Neolithic, and were almost always identified as wild [7,20,41—43,45,46]. The presence of domesticated pigs, based on size reduction, was recognized so far no earlier than Wadi-Raba times, almost 2000 years later (e.g. [16,39,42,43]). In southeastern Turkey pigs are almost as common as caprines and cattle [64,73], and sometimes even more common [24,38], since the PPNA and throughout the PPN. Based on size reduction, pigs were recognized as domesticated in Gurcutepe, as well as in Hayaz Tepe and Tel-Halula, by Peters et al. [64], as early as the late PPNB. This conclusion was questioned by Ervynck et al. [24]. In Çayönü, Ervynck et al. [24] found gradual and subtle changes in kill-off patterns, osteometry and Linear Enamel Hypoplasia frequencies, during more than 2000 years of the site occupation—PPNA to early PN. However, this gradual nature of the patterns was not tested statistically.

Hagoshrim provides the only opportunity in the southern Levant so far to study relatively big samples of pig remains from the PPNC to the end of the PN. Our results indicate that both kill-off pattern and morphometric changes occur simultaneously during the Wadi Raba period, as indeed has been found in other sites in the southern Levant [16,41—43,45,46]. The high occurrence of pigs in Layer 6, therefore, is best interpreted as intense hunting. According to the theory of cultural control, we would expect to find changes in kill-off patterns between Layer 6 and Layer 5, and perhaps also reduction in mean body size, preceding changes in shape. Yet, in the case of Hagoshrim, there is no indication that this was indeed the sequence of events. Thus, even with the theoretical framework and the appropriate statistical means, cultural control could not be inferred conclusively for pigs in the southern Levant. Possibly, a larger sample for Layer 5, would have revealed it as a transitional stage. Alternatively, the pigs of Layer 4 were not domesticated in situ, but were introduced to the southern Levant, probably from southeast Turkey. More assemblages from the early Pottery Neolithic and extensive comparisons with other areas in the Levant, as well as the integration of other criteria, are needed to further explore various models for pig domestication.

We introduced statistical methods to study the process of domestication, the contribution of which enabled us to tease apart different stages and aspects of this process. Hagoshrim provided a unique opportunity for a diachronic study of early animal domestication in the southern Levant. Use of our methods in other sites and assemblages will enable to fine tune our understanding of anthropological and evolutionary aspects of this highly influential process.

Acknowledgements

Appendix A

Table 1A
Summary statistics of morphometric data for caprines

	Element	N	Mean	sd	Min.	Max.
Layer 6	As-Gl	12	28.56	1.70	25.75	32.07
	Hu-BT	13	29.00	1.61	26.52	32.09
	Hu-HTC	6	14.61	1.60	12.78	17.83
	MC-BFd	8	26.60	4.19	21.83	33.22
	MT-BFd	3	24.94	4.04	21.05	24.67
	Ra-Bp	6	33.72	4.59	29.93	39.96
	Sc-GLP	3	30.61	1.11	29.32	31.28
	SC-SLC	3	18.90	0.44	18.42	19.28
	Ti-Bd	5	25.51	0.70	24.79	26.28
Layer 5	As-GL	7	27.69	0.93	26.59	28.97
	Ca-GL	6	57.39	0.01	55.00	59.71
	Hu-BT	29	29.37	0.03	25.99	33.60
	Hu-HTC	3	12.76	0.04	11.81	12.24
	MC-BFd	6	25.81	0.06	21.90	32.43
	MC-BFp	12	23.95	0.02	21.99	26.26
	MT-BFd	5	22.68	0.02	21.11	23.67
	Ra-Bp	13	31.45	0.04	26.96	36.98
	Sc-GLP	12	31.12	0.04	27.23	36.12
	Sc-SLC	13	19.02	0.02	17.26	20.93
	Ti-Bd	18	26.14	0.03	22.82	29.69
Layer 4	As-GL	11	26.58	1.22	23.68	27.85
	Ca-GL	10	57.33	4.51	50.31	63.29
	Hu-BT	81	29.11	2.13	24.09	34.40
	Hu-HTC	8	14.43	0.88	13.09	15.76
	MC-BFd	12	25.92	3.62	21.81	32.77
	MC-BFp	19	23.34	1.80	20.94	27.21
	MT-BFd	10	22.60	1.79	20.42	25.67
	Ra-Bp	48	31.92	3.17	24.39	43.39
	Sc-GLP	49	32.55	2.87	26.37	38.81
	Sc-SLC	24	19.19	1.77	16.25	22.81
	Ti-Bd	33	26.62	1.62	23.62	29.80

Appendix B

Table 1B
Summary statistics of morphometric data for cattle

	Element	N	Mean	SD	Min.	Max.
Layer 6	As-GLl	13	76.56	3.88	71.25	82.49
	Hu-Bt	4	81.92	7.31	76.50	92.38
	MC-Bd	2	69.49	7.65	64.08	74.90
	MC-Bp	8	64.23	6.20	55.09	76.59
	MT-Bd	2	65.16	8.56	59.10	71.21
	MT-Bp	4	51.39	0.90	50.46	52.46
	M/3-GL	1	40.13			
	ph1-Bp	14	35.54	4.11	30.43	44.01
	ph2-Bp	24	33.71	3.20	29.32	42.57
	T.NC-GB	5	62.48	4.68	57.52	68.44
	Ti-Bd	1	66.95			
Layer 5	As-GLl	9	69.45	4.72	64.32	79.11
	Hu-Bt	10	76.98	5.90	69.01	86.31
	MC-Bd	4	71.27	3.05	67.60	75.02
	MC-Bp	15	66.55	3.94	60.01	72.08
	MT-Bd	10	62.95	7.62	47.61	70.77
	MT-Bp	9	50.98	6.56	44.01	64.75
	M/3-GL	7	40.25	2.36	37.90	44.14
	ph1-Bp	17	33.02	4.12	25.05	39.60
	ph2-Bp	10	32.91	3.97	35.48	37.63
	Ra-Bp	4	90.13	11.94	74.52	103.21
	T.NC-GB	1	63.46			
	Ti-Bd	18	67.56	6.07	53.00	75.77
Layer 4	As-GLl	11	66.66	2.87	62.95	70.59
	Ca-GL	5	128.43	5.87	122.61	138.06
	Hu-Bt	4	79.62	7.91	68.13	86.07
	MC-Bd	13	63.44	4.55	57.44	70.71
	MC-Bp	11	60.26	3.15	54.53	65.90
	MT-Bd	20	58.09	4.89	52.25	69.54
	MT-Bp	6	45.12	0.53	44.31	45.89
	M/3-GL	6	38.82	2.03	37.14	42.84
	ph1-Bp	24	31.76	3.47	23.72	38.18
	ph2-Bp	45	31.34	2.76	26.21	36.65
	Ra-Bp	5	79.07	2.38	76.04	82.16
	T.NC-GB	13	59.33	4.72	52.68	66.01
	Ti-Bd	11	61.95	6.63	56.31	75.59

Appendix C

Table 1C
Summary statistics of morphometric data for pigs

	Element	N	Mean	SD	Min.	Max.
Layer 6	As-GLl	10	42.87	1.86	40.54	45.25
	As-GLm	5	40.81	0.63	40.03	41.76
	Ca-GB	5	24.32	1.97	20.84	25.53
	Fe-Bd	1	45.39			
	Hu-BFT	5	35.91	5.46	30.96	43.47
	MC 3′-Bp	4	19.20	1.79	17.44	21.09
	MT 4′-Bp	2	17.22	0.27	17.03	17.41
	MC 3′-Bp	5	18.24	0.63	17.64	19.28
	MT 4′-Bp	1	15.50			
	Ra-BFp	7	31.63	1.23	29.68	33.73
	Sc-GLP	12	38.02	4.53	26.54	42.68
	Sc-SLC	6	26.44	2.17	22.49	28.71
	Ti-Bd	5	34.45	3.04	31.23	38.58
	Ul-BPC	2	20.93	4.89	17.47	24.39

Table 1C (continued)

	Element	N	Mean	SD	Min.	Max.
Layer 5	As-GLl	7	43.75	2.92	39.73	48.41
	As-GLm	9	41.58	2.86	36.78	46.13
	Ca-GB	2	22.35	1.97	20.96	23.74
	MC 3′-Bp	8	20.24	2.47	16.40	23.69
	MT 4′-Bp	1	15.85			
	MC 3′-Bp	8	19.11	2.21	15.79	21.84
	MT 4′-Bp	2	16.69	0.92	16.04	17.34
	Ra-BFp	4	28.96	6.21	24.05	38.05
	Sc-GLP	10	40.81	5.61	32.64	48.76
	Sc-SLC	11	27.64	4.25	22.10	34.56
	Ti-Bd	4	33.10	3.32	29.68	37.22
	Ul-BPC	5	24.63	4.61	20.63	30.71
Layer 4	As-GLl	19	40.81	3.25	35.74	50.49
	As-GLm	18	38.45	3.28	34.51	48.44
	Ca-GB	22	21.00	2.17	15.72	25.44
	Hu-BFT	11	32.25	3.39	28.84	38.17
	MC 3′-Bp	18	17.63	1.43	15.15	20.58
	MT 4′-Bp	13	16.57	1.27	15.44	19.84
	MC 3′-Bp	13	15.24	1.60	12.71	18.52
	MT 4′-Bp	10	15.51	1.18	13.25	17.13
	Ra-BFp	20	29.01	2.50	24.91	36.65
	Sc-GLP	20	35.31	3.21	31.21	41.62
	Sc-SLC	17	23.21	2.03	20.22	28.16
	Ti-Bd	9	30.93	1.95	28.46	34.24
	Ul-BPC	16	21.09	2.35	17.21	26.85

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