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Production risk, inter-annual food storage by households and population-level consequences in seasonal prehistoric agrarian societies

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Using complementary behavioural and population ecological models, we explore the role of production risk, normal surplus and inter-annual food storage in the adaptations of societies dependent on seasonal agriculture. We find that (a) household-level, risk-sensitive adaption to unpredictable environmental variation in annual agricultural yields is a sufficient explanation for the origins of normal agrarian surplus and, consequently, of household-level incentives for inter-annual food storage; and, (b) at the population level, density-dependent Malthusian processes tightly constrain the circumstances under which this same mechanism can be effective in smoothing inter-annual fluctuations in household food availability. Greater environmental variation and higher levels of fixed set-asides such as seed requirements or transfer obligations to political authorities lead to more severe, periodic famines; however, outside of famine events, these same factors improve average population welfare by suppressing population density to levels at which Malthusian constraints have lessened impact. The combination of behavioural and population ecological modelling methods has broad and complementary potential for illustrating the dynamic properties of complex, coupled human–natural systems.

Keywords: risk, surplus, storage, prehistoric agro-ecology, food-limited demography, environmental anthropology

Introduction

Explaining the end-of-Pleistocene to early-Holocene transformations that resulted in stratified agrarian states remains a significant challenge to our understanding of prehistoric social evolution. We develop complementary behavioural and population ecological models to examine two elements proposed to be critical to socio-economic developments in this period: food production surplus and increasing dependence on inter-annual food storage. We find that stochasticity of yield in seasonal agrarian production provides sufficient explanation for normal surplus production and inter-annual storage by households, but that the success of this mechanism is tightly constrained by Malthusian dynamics at the population level. These results and the methods used to produce them advance understanding of the agro-economic processes affecting the dynamic linkages between environmental and human systems.

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Storage is prominent in diverse theories about the shift from hunting–gathering to food production, plant and animal domestication, sedentism, and the origins of social stratification and political centralisation (Angourakis *et al.* 2014; Earle and D'Altroy 1982; McCorriston and Hole 1991; Wesson 1999). Two reasons appear to be primary: storage is associated with the production of surplus and it commonly is archaeologically visible and measureable. Surplus is thought to underwrite developments such as socio-economic differentiation, an emerging but non-producing political hierarchy, private property and exploitation. However, because current evidence suggests that the energy yield (kcal) productivity of early cereal agriculture was lower than that of generalised foraging (Bowles 2011), surplus has proved difficult to explain in benefit:cost terms. The archaeological visibility of storage rests on the preservation of implements and facilities required for processing and containing the stored materials, and sometimes in the recovery of their residues. Conceptual reasons to assign importance to storage thus complement the pragmatic ones – it often can be observed and

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measured in ways that other factors in socio-economic theory cannot, at least in prehistory.

For instance, Testart (1982) argues that the combination of seasonality, abundance, efficient harvest and potential for effective storage led, at the end of the Pleistocene, to expanding food storage and sedentism with high population density and socio-economic inequality following as consequences.

> We have seen that the accumulation of wealth is *made possible* by sedentarism, *realized* by the transformation of food into lasting goods, and *rendered potentially unlimited* by the exchangeable nature of stored food (p. 526; italics original)

Storage is considered important even by authors (Ingold 1983) unwilling to assign it a primary causal role in these developments.

Regionally, subsistence intensification, surplus and storage are identified as key variables in socio-cultural evolution among the Creek in the southeastern United States (Wesson 1999), Andean Inka (Earle and D'Altroy 1982), interior British Columbia (Prentiss *et al.* 2014), the Yucatán (Carmean and Sabloff 1996), Mesoamerica in general (Smyth 1989), southwest Iran (Wright 1984), northern China (Barton *et al.* 2009) and the Levant (Garfinkel *et al.* 2009; Hald and Charles 2008). In the well-documented case of the Levant (Goring-Morris and Belfer-Cohen 2011), small-scale storage of wild foods, greater sedentism and expanding production of cultivated but undomesticated plant foods appear to have preceded and, through new means of risk reduction and intensification, to have facilitated later domestication. Domestication then is associated with expansion of storage facilities and population growth (Kuijt 2008), large-scale sedentary communities and social differentiation (Kuijt 2009). In parallel with these developments, storage moves from containers between houses, into houses and, eventually, into specialised rooms in houses (Kuijt and Finlayson 2009).

For purposes of this analysis, we define *storage* to be the curation of resources for delayed use. We focus on food resources stored for later consumption, but other agricultural or craft materials can be stored (Hendon 2000), and for eventual uses other than consumption. An example would be exchange. We distinguish between *intra-annual* food storage, a consequence of pulsed or uneven production measured over weeks or months, and *inter-annual* food storage of production that exceeds average annual consumption. In societies dependent on seasonal agriculture, intra-annual storage smooths consumption by making materials and foodstuffs available through the duration between harvests. By our definition, intra-annual stores are depleted at the end of the harvest cycle. We focus on the more problematic origins and dynamics of production sufficient for inter-annual storage, stored foodstuffs that outlast the harvest cycle.

We define *surplus* as production above annual household requirements, adjusted for expected shortfalls. Our definition formalises the observation by Allan (1965, 38; see also Halstead 1989) that African farmers typically cultivate an area sufficient to compensate for the possibility of a poor yield, thus producing a 'normal surplus' in an average year. Table 1 gives the name, symbol and descriptive characteristics of parameters and variables used in the text that follows, generally in the order in which they appear.

The household ecology of storage: variance compensation and surplus

The agrarian producer in a seasonal environment makes an irreversible investment in production by preparing fields and sowing a crop which, with attention and luck, will produce a varying and uncertain yield some 5–8 months later. If that crop is an important, dominant or perhaps the only source of dietary kcals, then the yield, after adjusting for unavoidable fixed set-asides, such as seed and obligations to political authorities, must feed the household through the duration of the period to the subsequent harvest. Planting decisions, field preparations and related investments become irreversible well before the farmer has evidence of the relative success or failure of the pending crop. Yield risk is one of the most salient features of agro-ecological production systems (examples in Cashdan 1990; Halstead and O'Shea 1989).

To model this situation, we draw on a risk-sensitive (Leslie and Winterhalder 2002; Winterhalder and Leslie 2002) analysis originally focused on fertility choices early in a family cycle, and the *variance compensation hypothesis*. At planting the agrarian producer makes an agricultural investment anticipating that the outcome must provide for a fixed set-aside and household consumption needs, p_b. An outcome short of fixed set-asides and household needs is consequential in hunger and perhaps debilitating, even mortal, deprivation for the months to come. An outcome in excess of the minimal requirement represents unnecessary expenditure of labour and materials, but erring on the upside of needs has much lower salience for welfare than falling to the downside.

In this circumstance, variance compensation leads the household to over-produce and *to do so to a degree that exceeds adjustment for its expected or average shortfall*. This excess production constitutes a form of normal surplus with potential importance to early socio-economic evolution. The household level, risk-minimising tactic is to avoid the dramatic negative consequences of falling short of needs by accepting the

Table 1 Parameters used in the variance compensation model*

Symbol	Description	Value(s)	Notes
p_b	Baseline agricultural investment	$p_b \in R^+$	TIP (field preparation, seed, weeding etc.) that under ideal, non-stochastic conditions would match with perfect certainty optimum household requirements for yield, measured in output units (kg corn) for a hypothetical household
p_e	Expected or average loss investment	$p_e \in R^+$	Addition to the TIP needed to offset average *expected* losses under a specified level of stochastic variation in yields and thus meet baseline household requirements
p_v	Variance compensation investment	$p_v \in R^+$	Further addition to the TIP needed to adjust for asymmetry in the value function associated with stochastic outcome variance
α, β	Shape parameters of the Beta distribution	$\alpha \in R^+$, $\beta \in R^+$	Where $$\text{Beta}(x) = \frac{x^{\alpha-1}(1-x)^{\beta-1}}{\frac{\Gamma(\alpha)\Gamma(\beta)}{\Gamma(\alpha+\beta)}}$$ and $\Gamma(z)$ is the gamma function
μ, ϕ	Mean and dispersion of reparameterised and more intuitive Beta distribution (see Ferrari and Cribari-Neto 2004) used in Table 2	$\mu \in (0,\ 1)$, $\phi \in R^+$	Where $$\mu = \frac{\alpha}{\alpha+\beta} \text{ and } \phi = \alpha + \beta$$ and $\phi = 13.4$, determined empirically from wheat yields in preindustrial England (Campbell 2007)
M, N	M is the peak of the value function; N is the dispersion parameter for the value function	$M \in R^+$, $N \in R^+$	M is the estimated amount of resource required to meet the kcal requirements of a small household, set for purposes of our simulation to 700 kg (see p_b); N is set arbitrarily to 200, in order to illustrate a moderately asymmetrical value function (see Fig. 1(b))
$\boldsymbol{\theta}$	Matrix of output units	$\boldsymbol{\theta}_{[i,\,j]} \in R^+$	$$\boldsymbol{\theta}_{[i,j]} = \Sigma(\text{Random Beta}(j, \alpha_{[i]}, \beta_{[i]}))$$ Simulated array of yields calculated for combinations of Beta results over $\alpha_{[i]}$ and $\beta_{[i]}$ and input units j
$\boldsymbol{\Phi}$	Matrix of relative fitness units	$\boldsymbol{\Phi}_{[i,\,j]} \in (0,\ 1)$	$$\boldsymbol{\Phi}_{[i,j]} = e^{\left(\frac{M^2}{(M-N)^2} - \frac{M\theta_{[i,j]}}{(M-N)^2}\right)} \boldsymbol{\theta}_{[i,j]}^{\left(\frac{M^2}{(M-N)^2}\right)} M^{-\left(\frac{M^2}{(M-N)^2}\right)}$$ Simulated array of fitness results as a product of stochastic yields ($\boldsymbol{\theta}_{[i,j]}$) and the value function illustrated in Fig. 1(b)

*R^+ represents the positive real numbers. Further details in text and supplemental materials; (see Puleston *et al.* 2014, Fig. 1 and Table 1) for details of the parameters and variables used in the population ecology model.

lesser cost of over-investment that routinely exceeds those needs. Unpredictable yields and asymmetric valuation of outcomes leads to bet hedging to a large degree.

Fig. 1(a) (see also Table 2) presents an array of Beta distributions representing the probability of unit level yield outcomes as a function of worsening agricultural conditions. In a perfect world, the farmer would know precisely what yield to expect from each unit of inputs. Other conditions constant, a fixed seed ratio would represent a basic form of this expectation. The farmer would invest confidently in an input package targeted to produce 700 kg of crop and she would get 700 kg. We call this the targeted input package (TIP), and note that the figure of 700 kg is arbitrarily chosen to represent the approximate subsistence production needed by a family household.

More realistically, the farmer knows only that conditions will not be ideal and the resulting crop generally conforms to a frequency distribution with an expected value and range. That distribution will depend on a particular combination of environment, cultivar, production technology and farmer skills, and it may rest at the relatively high $\mu = 0{\cdot}71$ or low $\mu = 0{\cdot}29$ end of the potential range. For example, if the Beta mean is $\mu = 0{\cdot}71$, the farmer aiming *on average* for the household baseline needs would invest in a TIP equal to 908·6 kg production (700 kg + 208·6, or baseline plus the supplement required to offset expected average losses, p_e; see Table 2).

Fig. 1(b) represents the *value* of various yield outcomes to the farm household, still using 700 kg as the annual baseline consumption requirement. We assess value as fitness although it could be utility or any like metric. The shape of this function formalises the belief that falling short of the baseline yield is more costly than overshooting it. At 300 kg, the family faces severe hunger; if it must also allow for fixed set-asides, its survival may be threatened. At 1,100 kg, the household may have regret in hindsight

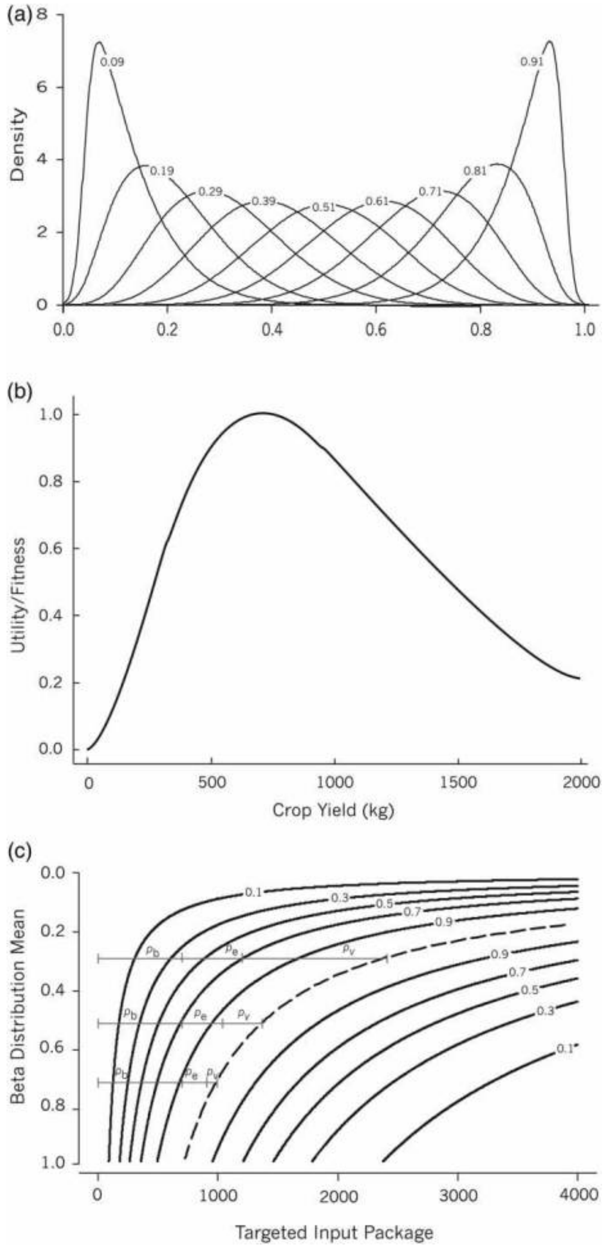

Figure 1 (a) Risk-sensitive, variance compensation for seasonally pulsed, agrarian yields. (a) Beta densities declining from $\mu = 0{\cdot}91$, to $\mu = 0{\cdot}09$, with ϕ fixed at 13·4 represent increasingly challenging, stochastic environmental conditions affecting yields. The *y*-axis is probability density; the *x*-axis is output per unit input. (b) Value in units of fitness/utility as a function of realised output. The asymmetric shape of this function formalises the assumption that there is a steeper cost to falling short of needs than to exceeding the household optimum of 700 kg. (c) Variance compensation, iso-fitness contour map representing fitness or utility as a function of a TIP (*x*-axis), the value function, and increasing environmental challenge (*y*-axis), as modelled with Beta distributions. Inputs (measured as the target production they would yield under ideal conditions) are parsed into the amount required to meet baseline annual requirements (p_b), offset mean expected shortfalls (p_e), and offset variance compensation arising from asymmetry in the value function (p_v). See Table 2 for values.

at having worked too hard the previous planting season, but it does not face a subsistence crisis. Because there are opportunity costs to over-production there is a modest downturn of the value function as it moves to the right past the baseline requirement, but it is not nearly as steep of a decline as that for under-production.

Fig. 1(c) is the product of the outcome distributions and value function. It represents a risk-sensitive analysis of the household's subsistence choice as an iso-fitness contour map, with fitness calibrated to a 0, 1 scale. The *x*-axis is the critical farm decision, what is the optimal TIP. More specifically, what is the best, risk-sensitive input package, assessed as the yield it would generate under ideal and completely predictable conditions? Ascent up the *y*-axis represents decreasing mean yield outcomes (Table 2, μ). The optimal investment strategy under a given outcome distribution lies on the rightward-tending ridge that begins with baseline family needs and completely predictable yield of $x = 700$ kg at $y = 0$. More realistically, as conditions worsen and stochastic afflictions of the crop mount, μ declines, and the ridge curves strongly to the right, requiring that the farmer compensate by overplanting.

Variance compensation impels the farmer to invest in overplanting to a larger degree than is required simply to offset *average* expected shortfalls. To demonstrate, in Fig. 1(c) (see also Table 2) we parse the optimal TIP into the baseline portion p_b, the risk-sensitive portions required to offset expected *average* shortfalls p_e, and the portion required to offset the asymmetry of the underlying value function p_v. As the Beta distributions fall away from the most propitious circumstances, the variance compensation component p_v of the farmer's adjustment grows substantially. Returning to our earlier example of $\mu = 0{\cdot}71$, a full risk-sensitive analysis adds a variance compensation component p_v=86·4 kg to the farmer's input package target, which now stands at 995 kg ($p_b + p_e + p_v$=700 + 208·6 + 86·4). As is evident in Table 2, p_v grows rapidly as agrarian conditions worsen. We consider p_v to be a key element of normal surplus and an adaptive feature of seasonally pulsed agrarian production that is critical to a form of livelihood subject to unpredictability. It is a sufficient explanation for the normal surplus that underwrites inter-annual food storage.

The population ecology of storage

Household food security in a seasonally pulsed agrarian system requires over-production to a degree that implies inter-annual storage of a normal surplus. We now consider surplus and inter-annual storage at the level of a population living in a space-limited environment over the long term. We use a second, somewhat different but complementary, modelling approach based in population ecology and simulation.

Table 2 Beta distribution parameters and properties, and their variance compensation effects

Beta parameters and properties				Variance compensation				
α	β	Mean μ	Variance	Risk-sensitive input	Input above (700 kg)	p_e	p_v	$\frac{p_v}{p_e}$
11·82	1·18	0·91	0·006	763	63	57·3	5·7	10·0%
10·50	2·50	0·81	0·011	871	171	138·1	32·9	23·8%
9·19	3·81	0·71	0·015	995	295	208·6	86·4	41·4%
7·88	5·12	0·61	0·017	1162	462	280·2	181·8	64·9%
6·57	6·43	0·51	0·018	1370	670	338·6	331·4	97·9%
5·12	7·88	0·39	0·017	1801	1101	433·5	667·5	154·0%
3·81	9·19	0·29	0·015	2411	1711	501·8	1209·1	240·9%
2·50	10·50	0·19	0·011	3662	2962	568·2	2393·8	421·3%
1·18	11·82	0·09	0·006	NA	NA	NA	NA	NA

Distributions depicted in Fig. 1(a). α and β are the shape parameters for a Beta distribution, reparameterised here to use a more intuitive set of mean, μ, and dispersion parameter, ϕ (Ferrari and Cribari-Neto 2004; see also Supplemental Materials). p_e = portion of extra production covering expected average loss, p_v = portion attributed to variance compensation. NA = conditions so poor that variance compensation is ineffective in achieving household baseline yields.

This model tracks interactions among an age-structured population and environmental parameters that describe agricultural yields and population food requirements. Under the parameter conditions specified, age-specific returns to labour determine agrarian production and age-specific consumption requirements determine total food demand of the population. Food availability conceptualised as a *food ratio E* – kcals available from production divided by those needed for consumption to sustain fertility and mortality at optimal rates – determine age-specific survival and fertility, and thus an updated age structure and population size, completing a cycle of the simulation. Model parameters are set to values believed to be representative of prehistoric agrarian peoples (Lee *et al.* 2006); model dynamics depend to large degree on the food ratio E. So long as $E \geq 1$, fertility is high and mortality low and the population grows at a constant rate. As the environment, idealised as 1000 arable ha, is filled, land availability shrinks while interference and exploitation competition grow. As E declines below 1, decreased per capita food availability elevates mortality and depresses fertility, leading eventually to a stable age structure and a Malthusian equilibrium at which the growth rate is zero (full details in Kirch *et al.* 2012; Lee *et al.* 2009; Lee and Tuljapurkar 2008; Puleston and Tuljapurkar 2008; Puleston *et al.* 2014).

For the present analysis, we incorporate stochastic environmental variability into the model. Population-level yields are determined by independent random draws from a symmetrical Gamma distribution with a mean of 21,000 kcal/ha/day and a coefficient of variation (CV = standard deviation/mean) of either 0·2 or 0·3. CV = 0·2 is on the low end of variation typical for dry farming (Lee *et al.* 2006); CV = 0·3 is representative of the variation associated with English cereal production in the 14th century (Campbell 2007). Unpredictable yield variation leading to food crises was a recurrent feature of early agriculture (Hayden 1981; Schibler and Jacomet 2010). While an observant farmer might with sufficient experience surmise the underlying distribution and thus the central tendency and range of variation in yields, he or she has only odds to associate with a particular outcome. In our model, those odds are set by the Gamma distribution's CV.

Novel to the present analysis is an assumption of risk-sensitive households and inter-annual storage of normal surplus. We conceptualise inter-annual storage as follows. In year x, any harvest above what is required to meet the population's intra-annual food requirements at the level of $E = 1$ is considered an overage and can be carried forward to the next year. In year $x + 1$, the carry-forward is consumed first. If the carry-forward falls short of requirements in that year, the deficit is made up from current year $x + 1$ yield, and any remainder then becomes overage to be carried forward to year $x + 2$. If the first year carry-forward exceeds year $x + 1$ requirements, any excess is lost and the carry-forward to $x + 2$ is the entire year $x + 1$ production. This approach imputes to the crop a maximum shelf life of 2 years from the date of its harvest, the cut-off being a simple way of allowing for loss from pilfering, spoilage and vermin (Puleston 1971; Smith and Kenward 2011, 2012). A longer shelf life or a more complicated manner of representing the fate of stored foodstuffs are both possible but would complicate this initial analysis and are left to future studies.

Table 3 presents quantitative summaries averaged over the last 300 years of 10 simulations at CV = 0·2 and CV = 0·3, each simulation 700 years in duration. We sample from the later portion of the simulations in order to render moot the influence of starting conditions; the values shown represent the population at a quasi-stable, Malthusian equilibrium. We show results for four combinations of factors: no fixed set-asides above family consumption, and fixed set-aside rate of 40%, each of these two scenarios with and without storage. Fixed set-asides represent production

Table 3 Population and welfare effects of fixed-cost set-asides and storage

Set-aside	Storage	$\bar{E}$	$\bar{N}$	Frac $E \geq 1$	e_0 (years)	Death rate	Granary (kcal)
CV = 0·20							
No set-aside	No	0·74 (0·21)	12,080 (0·05)	0·06	32·8 (0·30)	0·033 (0·51)	–
	Yes	0·74 (0·21)	12,142 (0·05)	0·06	32·8 (0·31)	0·033 (0·51)	$5{\cdot}43 \times 10^7$ (5·35)
40% set-aside	No	0·79 (0·26)	8,853 (0·08)	0·14	34·2 (0·32)	0·033 (0·71)	–
	Yes	0·80 (0·27)	9,091 (0·08)	0·16	34·2 (0·33)	0·033 (0·70)	$1{\cdot}86 \times 10^8$ (3·12)
CV = 0·30							
No set-aside	No	0·85 (0·31)	10,565 (0·10)	0·26	35·3 (0·34)	0·033 (0·83)	–
	Yes	0·87 (0·34)	11,208 (0·09)	0·29	35·4 (0·34)	0·033 (0·85)	$6{\cdot}11 \times 10^8$ (2·32)
40% set-aside	No	1·06 (0·43)	6,058 (0·25)	0·50	37·9 (0·31)	0·033 (1·28)	–
	Yes	1·11 (0·49)	7,970 (0·16)	0·51	37·8 (0·32)	0·033 (1·25)	$1{\cdot}46 \times 10^9$ (1·48)

Values derived from the last 300 years of a 700-year simulation, averaged over 10 runs, representing system dynamics in a quasi-stable equilibrium (CV = 0·2 and CV = 0·3). Coefficients of variation in parentheses. $\bar{E}$=average food ratio; $\bar{N}$=average population size; Frac $E \geq 1$, the fraction of the 300 years for which the food ratio is equal to or greater than 1; e_0 is average period life span; death rate is the average fraction of the population that dies of any cause in a year; Granary [kcal/year] gives the average inter-annual holdings in the granaries. One run from the 10 (40% set-aside scenario) is shown as a 300-year time-path in Fig. 2 (CV = 0·2) and one in Fig. 3 (CV = 0·3).

that is removed from the pool available for consumption by producers, and allow us to examine the effect of factors like seed requirements or payments owed to political elite. The 40% fixed rate is not 40% of total production, but rather 0·4 of the maximum fixed-cost rate that the population could sustain in an environment that provided constant yields. Put differently, this corresponds to a total set-aside of $3{\cdot}82 \times 10^6$kcal/day, or approximately 22% of the typical production on 1000 ha in the CV = 0·3 environment without a storage regime.

At CV = 0·2 and no set-aside, storage has virtually no effect on average food ratio $\bar{E}$, it increases marginally the average population size (12,080–12,142), but it does not perceptibly change average population welfare, assessed in our model by (a) the frequency of years in which food consumption is at or above the level providing for optimum fertility and mortality (Frac $E \geq 1$), (b) life span (e_0) and death rate (definitions in Table 3 note). Inter-annual storage available as carry-over to fill the granaries averages $5{\cdot}43 \times 10^7$ kcal, or approximately enough to supply all of the caloric needs of 68 people for a year at a rate of 2,200 kcal/ind/day. Imposing a set-aside requirement at this level of stochastic variation improves average food ratio ($\bar{E}$), sharply diminishes average population size and improves measures of population welfare. Frac $E \geq 1$ is better than doubled, from around 6 to 15%. Mean life span e_0 is increased by 4·3%, from 32·8 to 34·2. Average kcals put into inter-annual storage increases by a factor of 3·4 to $1{\cdot}86 \times 10^8$. Average death rate remains the same across these four comparisons (0·033 annual deaths per capita), but the CV of death rate rises with a set-aside (0·51–0·71).

The sharp drop in average population size with set-asides is expected, as the diverted kilocalories would otherwise support the producing population (Puleston and Tuljapurkar 2008). Less intuitive are the improvements in welfare, all of which arise from the observation that a fixed set-aside exaggerates variability in residual foodstuffs available for consumption, exacerbating the magnitude and thus effects of famines and, by suppressing average population size, reduces the impact of Malthusian constraints. Fewer people and more effective use of labour in production also mean that there are more kcals left over at the end of the agricultural cycle, raising the quantity that goes into inter-annual storage and available to ameliorate the impact of shortfalls. Average death rate remains the same – a consequence of our sampling from quasi-equilibrium demographic conditions – but year-to-year variance increases due to heightened volatility in food availability and the sharper consequences of famines.

We observe that the same patterns are associated with storage and set-aside within the CV = 0·3 results (Table 3). Comparing CV = 0·3 with CV = 0·2 within each of the four scenarios (set-aside or not, with or without storage), higher environmental variation reduces population size and enhances mean measures of welfare. The combination of CV = 0·3, a set-aside and storage actually raises the average food ratio above baseline, to $\bar{E} = 1.11$. The population – although the next to smallest in numbers – enjoys a surfeit (defined as Frac $E \geq 1$) in 51% of the simulated years. This helps to support and is partially the consequence of a 2·4-fold increase in the number of kcals set-aside in inter-annual storage from $6{\cdot}11 \times 10^8$ to $1{\cdot}46 \times 10^9$. Life span has increased modestly; average death rate remains the same. The variability in both has increased.

Fig. 2 shows a 300-year history from one of these simulations, the CV = 0·2, 40% fixed set-aside scenario. Reading from bottom to top, the panels show the time course of the simulated yields (Fig. 2a), along with population mortality with storage (Fig. 2b) and without (Fig. 2c) storage, the amount of food (kcals) held in storage (Fig. 2d), and the food ratio E_t (Fig. 2e) and population size N_t

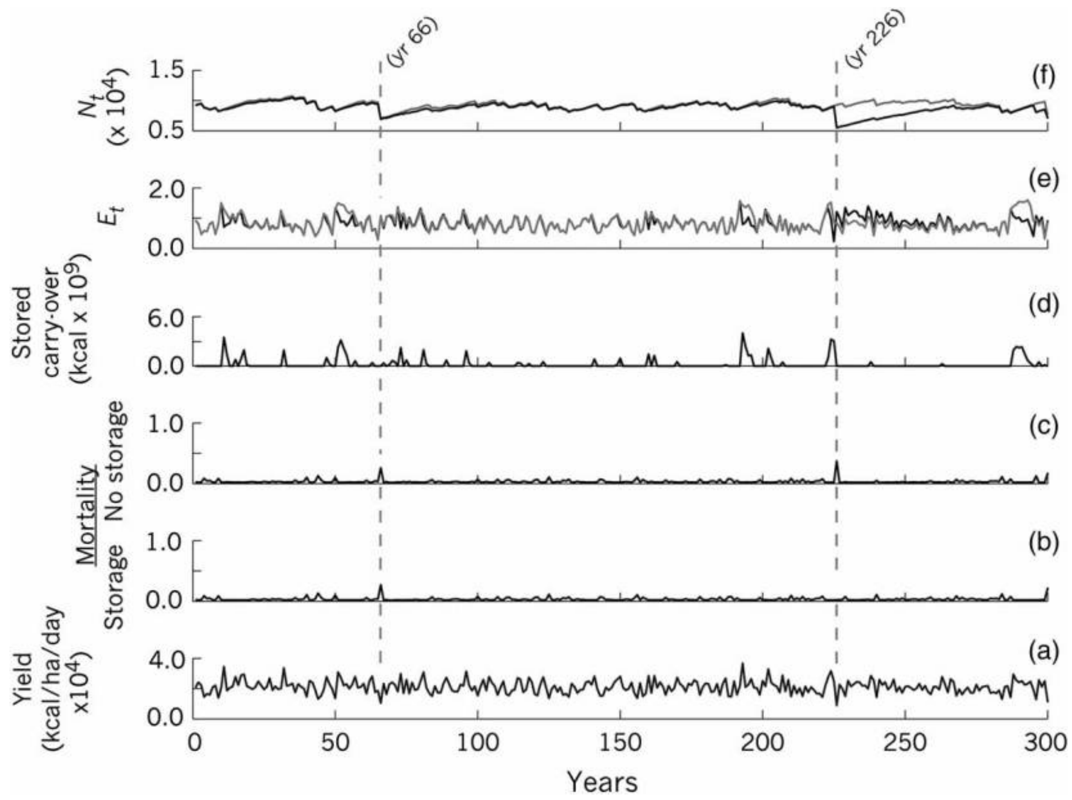

Figure 2 Time series of environmental variation and population response (CV = 0·2). Panel (a) gives Gamma distribution, yield variation, (mean = 21,000 kcal/ha/day, CV = 0·2); panels (b) and (c) show annual mortality for the storage and no-storage scenarios, respectively; panel (d) shows how much inter-annual carry-over of food was stored each year (kcals); panel (e) tracks the food ratio (*E*) and panel (f) the size of the producer population for the storage (grey) and no-storage (black) scenarios. Discussion in the text.

(Fig. 2f) both with and without storage. With the exception of a 50-year period beginning in year 220, the storage and no-storage populations are almost perfectly coincident (Fig. 2f). In general, storage appears to have little effect on the population trajectory at CV = 0·2. This reinforces our reading of Table 3; at this low degree of variation, storage is of limited but not negligible consequence for average population size and welfare outcomes.

Although averages are similar for the storage and no storage scenarios, specific historical contingencies can lead to divergent trajectories over the short term. Years 66 and 226, the two most extreme downward spikes in yield (Fig. 2a), present an interesting example. In year 66, storage has almost no impact on famine mortality and it does not diminish a precipitous decline in population, whereas in year 226 storage eliminates famine-induced mortality altogether, preventing a population decline. By chance year 66 is preceded by several years of low yields (Fig. 2a) in which $E < 1$ (Fig. 2e), leaving the granaries empty or nearly so (Fig. 2d) when the famine year hits. In contrast, year 226 is preceded by several years of $E > 1$; yields have been abundant and the granaries are well stocked and thus able to buffer the crisis year. The short-term consequences are evident in the population trajectories from year 66 and 226 forward.

Table 4 shows the mortality rates for the year 66 and year 226 famines under our four scenarios. In year 66, storage has no effect in the no set-aside and fixed set-aside scenarios. In year 226, storage reduces famine mortality in all scenarios, strikingly so in the case of a fixed set-aside.

In Fig. 3, we illustrate a similar time series with yield CV = 0·3. Yield variance is greater (Fig. 3a), as are spikes of famine-induced mortality (Fig. 3b and c). Granaries are fuller, more of the time (Fig. 3d). Periods of ample stores appear to persist for approximately 10 years duration interspersed among long stretches of empty or nearly empty granaries. The food ratio is consistently higher (Fig. 3e) but average population is lower (Fig. 3f). The size of the food-storing population is significantly elevated over its non-storing alternative, especially after the famine in

Table 4 Famine year consequences for mortality of set-asides and storage (CV = 0·2)

Tax policy	Event	Famine mortality (no storage:storage)
No set-aside	Yr 66	0·17:0·17
	Yr 226	0·22:0·16
40% set-aside	Yr 66	0·26:0·27
	Yr 226	0·37:0·04

Mortality defined as death rate. The 40% set-aside results correspond to Fig. 2.

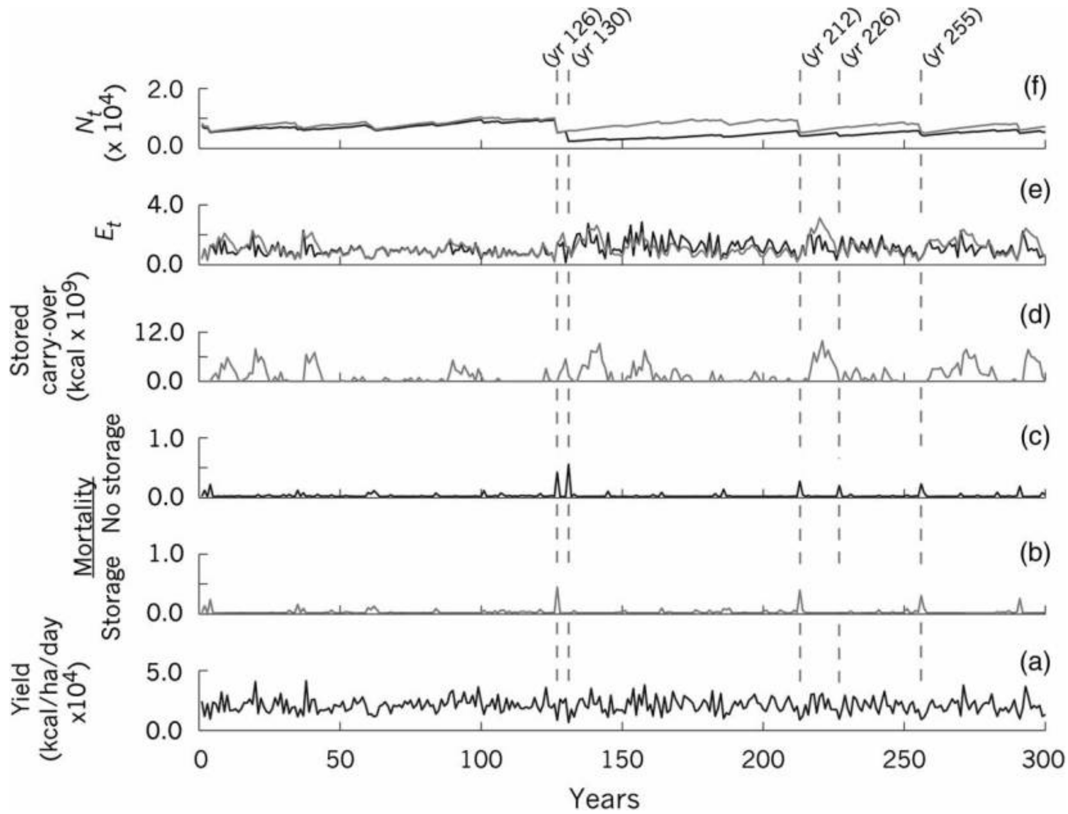

Figure 3 Time series of environmental variation and population response (CV = 0·3). Panels defined as in Fig. 2.

year 130. All of these trends are consistent with the averaged results of 10 simulations presented in Table 3 (CV = 0·3; 40% set-aside).

The historical contingency of storage effectiveness is well illustrated in this series. Storage provides little or no protection in years 126, 212 and 255; it is highly effective in years 130 and 226 (Table 5). When storage fails in a food-storing population, death rates actually are higher than would have been suffered by a non-storing population under the same yield shortfall. This can be seen by comparing storage with non-storage death rates for years 126, 212 and 255). This occurs because the food-storing population typically enters the famine year at a larger size (Fig. 3f).

It is an unexpected result of the Malthusian, density-dependent situation that fixed set-asides in a context of fluctuating yields lessens average hunger, increases the frequency of food-abundant years, lengthens lifespan without significantly changing death rates, and elevates the demographic benefits of storage. Each of these results derives from the shift to less frequent but more severe famines under fixed-cost scenarios, resulting in long periods of efficient labour productivity and high E as the recovering population only slowly approaches Malthusian constraints on its size. Storage augments these positive effects on measures of average welfare, although it worsens the impact of famine when it fails to buffer a shortfall. Long-term average population size falls, the decline somewhat offset *within* each case by storage, as an increasing portion of yield is deflected away from sustaining the consumption needs of the producing population. Malthusian processes dominate the logic of storage as well. Because the population spends the great majority of its time below $E = 1$, years in which there is something left over to store are uncommon, especially if there are no set-asides (see Fig. 2d; Table 3, Frac $E \geq 1$).

Table 5 Famine year mortality with and without storage (CV = 0·3), 40% set-aside

Year	Famine event mortality rate	
	No storage	Storage
126	0·42	0·45
130	0·55	0·02
212	0·27	0·40
226	0·20	0·02
255	0·23	0·30

Mortality defined as death rate. The results depicted here correspond to Fig. 3.

Discussion

Through complementary modelling approaches, we seek a fuller understanding of production risk, storage dynamics and population ecology commensurate with the complex role production intensification and delayed-return is thought to play in the household and population-level evolution of subsistence and social stratification. At a more general level, we aim to advance the integration of methodologies useful in understanding the dynamics of human systems (Kirch *et al.* 2012; Kohler and van der Leeuw 2007; Liu *et al.* 2007; McConnell *et al.* 2011; McPeak *et al.* 2006) and the impacts of these dynamics on the analysis of the archaeological record documenting social evolution (Lake 2014).

Risk-sensitive adaptation, normal surplus and storage

Growing dependence on a seasonal pulse of agrarian production compels household adaptation through over-production to offset expected average shortfalls *and* the effects of variance compensation. Asymmetric valuation of outcomes is a critical element of household adaptive dynamics. Risk-sensitive planting decisions provide a sufficient explanation for normal surplus, and for storage facilities dedicated to inter-annual carry-over of foodstuffs. The variance compensation component of surplus and storage will be enlarged to the degree that seed set-asides, involuntary payments to political elites and perhaps other fixed factors must be added to consumption needs. Variance compensation likewise will be augmented by the degree of seasonality and the population's dependence on seasonal foodstuffs (McCorriston and Hole 1991), especially for societies in marginal, rain-fed agricultural zones (e.g., Charles *et al.* 2010).

The shift from immediate- to delayed-return production (Woodburn 1982) that we highlight is generally but not necessarily coincident with the shift from hunting–gathering to agricultural modes of subsistence. However, foragers living in habitats in which a dominant dietary resource arrives in an abundant seasonal pulse, e.g., salmon runs for Native Americans living on the Pacific Northwest coast, may have invested in obtaining a surplus and have stored significant quantities of the resulting harvest. All else equal, our model would predict inter-annual storage in this situation; from a risk-sensitive perspective their production system is like that of seasonal farmers (Testart 1982, 530). Likewise, agriculturalists living in the aseasonal tropics maintain garden plots that yield on a day-to-day basis throughout the year. For our purposes, they are like foragers who gather their cultivars, and we would not predict that they practice inter-annual storage as a mechanism for adapting to production risk.

The late-Pleistocene, early-Holocene transition from foraging to farming was variable in duration and sometimes prolonged. Mixed-production systems reliant on shifting combinations of foraged, hunted and cultivated foods persisted in some cases for thousands of years (Smith 2001). This requires that we be cautious about simple contrasts between immediate- and delayed-return societies, especially those rendered as hunter–gatherers versus farmers. Variance compensation and its effects will grow in importance as year-round dependence on a seasonal, delayed-return pulse of yield increases, but continued immediate-return foraging and fallback foods may hold back such developments for an extended period of time.

There may be archaeologically visible manifestations of variance compensation in food processing for storage and in storage facilities. Even without the risks associated with unpredictable variations in annual yield, a seasonal pulse of yield must be conserved through the year in order to feed the household. Variance compensation predicts storage facilities large enough to accommodate this baseline production (p_b), as well the surplus production required of risk-avoidance ($p_e + p_v$), the total adjusted for fixed set-asides and complementary sources of food.

Finally, we observe that the normal surplus which results from risk-sensitive household adaptations has socio-political consequences for the evolution of property concepts, resource extraction by elites, status differentiation and hierarchy. We claim here that variance compensation is a *sufficient* explanation for household production of inter-annual surplus requiring storage from one year to the next. However, our model does not address how this surplus may have

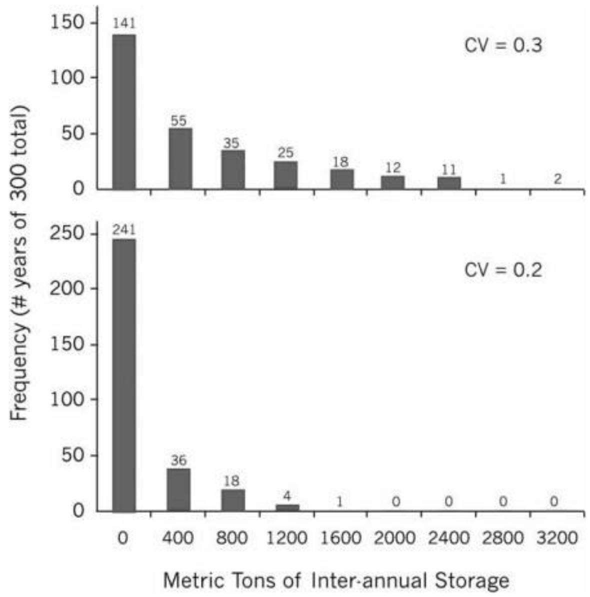

Figure 4 **Frequency distribution of population-level, inter-annual storage for CV = 0·2 and CV = 0·3 environments, fixed set-aside scenarios. The leftmost bar shows the number of years in which previous year carry-over plus production was not sufficient to exceed population needs at $E \geq 1$, thus no inter-annual carry-over was placed into storage. The bars to the immediate right shows the amount of food in carry-over inter-annual storage when it occurred, binned in increments of 400 metric tons, dry weight wheat equivalents. In the CV = 0·2 scenario 241 (or 80·3%) of the years have no inter-annual storage; in CV = 0·3, the corresponding value is 141 years (47·0% of the total). See Figs. 2 and 3 for the time series from which these results were drawn.**

been conceptualised and defended by its producers or how some portion of it came to be exploited by elites (Hendon 2000).

The population ecology of inter-annual surplus or Malthus stalks the granary

In a situation of volatile yields and Malthusian, density-dependent feedbacks on population, our population-level model suggests that household storage facilities were only intermittently stocked (Fig. 4). Even with fixed set-asides and CV = 0·3, our simulated granaries were empty almost half of the time (141 of 300 years). Increasing yield variation increases the frequency with which granaries are stocked. This is not necessarily because need is greater – in fact need may be less because the population is smaller and production more efficient (Table 3) – but because normal surplus and thus opportunities to hedge are more frequent. We need keep in mind that although stocked, granaries may have fallen short of the quantity of provisions that would fully achieve the insurance benefits of inter-annual carry-over.

Bogaard *et al.* (2009) calculate that the average 1 m^3 storage bin at Çatalhöyük would provision a family for approximately a year. Unless other staples are making a significant contribution to diet, and neglecting the possibility of more perishable containers and forms of storage, this would only allow for average intra-annual provisioning, not for risk-sensitive adjustments or inter-annual storage past that the next harvest, should it be a poor one. At its fullest point in the agricultural cycle, harvest time, a risk-sensitive granary would have sufficient volume to cover baseline requirements, p_b, plus the two components of a risk-sensitive allowance, p_e and p_v, and allowance for inter-annual carry-over. Even if baseline requirements for stored food are known, the highly skewed distribution of storage volumes arising from our simulations (Fig. 4) provides guidance, but also presents a challenge to efforts to calculate the size of a risk-sensitive storage facility.

The effect of an especially bad year on population levels depends heavily on the yields in the several years that come before. The divergent population histories following year 66 and year 226 (Fig. 2f) provide an example. Yield shortfalls exacerbated by set-asides induce periodic famines but coincidentally have the consequence of releasing a population from the relentlessly unhappy pressures of high mortality, low fertility and relative hunger associated with a Malthusian equilibrium (Table 3; Figs. 2 and 3) in the decades that follow. Increasing yield variability from CV = 0·2 to 0·3 results in higher average human welfare [$\bar{E}$, Frac e_0, e_0 (lifespan)], lower average population size ($\bar{N}$), an unchanged death rate, and fuller granaries (Granary Avg [kcal]). These average indicators also improve with increases in fixed set-asides. Storage is effective when a serious famine year follows several good harvests and granaries are full; however, that same society will suffer greater mortality than its non-prudent, non-storing counterpart if the famine happens to follow several relatively lean harvests (Table 5). Granaries were often only partially full and occasionally completely depleted as a new agricultural harvest approached.

Counter-intuitive elements in these observations suggest caution in that we are just beginning to understand the dynamics that link ecology and climate, crop production, household behaviour, population ecology and political obligations, what Schulting (2010, 160) calls the ‘chain of causality’ between environment and socio-economic change. Prehistorians disagree as to whether or not population pressure is a cause of major post-Pleistocene transformations (compare Cohen 2009; Hayden 1981). It is a debate that will be hard to resolve successfully without our clearly sorting out the consequences of density dependence when brought into interaction with yield variation, vital rates, surplus, storage and fixed-cost set-asides (Smith and Kenward 2011, 257). The potential interactions are more complex than have been recognised, the dynamic properties of this model system hinting at complexities commensurate with the diversity of historical trajectories among early food-producing societies.

Assumptions and constraints

A model is an expedient compromise with our understanding of reality, useful but also hazardous if used without awareness of the assumptions and constraints that underlie it (Lake 2014; Winterhalder 2002). Here, we seek a heuristic understanding of mechanisms or processes whose dynamics are thought to be important to social evolution (Barton 2014, 311). We rely on assumptions basic to the risk-sensitive (Leslie and Winterhalder 2002; Winterhalder and Leslie 2002) and food-limited approaches (Puleston and Tuljapurkar 2008; Puleston *et al.* 2014) that inform our analyses. We make several additional, important simplifying assumptions. In our risk-sensitive model, we represent environmental stochasticity with a Beta distribution (Fig. 1(a); see Supplemental Materials). We parameterise the Beta distribution with values characteristic of seasonal, rain-fed temperate zone cereal agriculture, drawn from empirical study of medieval agricultural yields of wheat, barley and oats in southern England (Ross n.d.), and we note that the values for other agro-ecological systems, crops and regions presumably will differ. We assume a singular, idealised household type, meaning our model does not recognise variation in household consumption requirements, labour availability, skill or access to productive resources. We provide our households choice over only one agro-economic option for avoiding production risk, their TIP, modelled as a fixed time input to agriculture sufficient to generate a surplus at low population densities. They do not, for instance, have the option of insuring through use of back-up food sources (Schibler and Jacomet 2010), exchange, pooling (Winterhalder 1990) or other means.

In our population ecology storage model, we use independent random draws from a Gamma distribution to represent yield stochasticity. This effectively homogenises the spatial dimension of the agricultural environment and eliminates the possibility of temporal auto-correlation among environmental states. Households adopt and repeat the same planting strategy every year, irrespective of how much they have in storage. In effect, households do not have the contingent possibility of adjusting their agricultural strategy as a function of their current state, specifically, their current food stores. We do not consider the social dilemmas of household contributions to cooperative or pooling storage (Angourakis *et al.* 2014), nor do we attempt here to include in our model important relationships among surplus, storage, socio-economic practices, the distribution of political power or moral understandings of property (Hendon 2000). We are confident that most of these assumptions will not affect the structural results we describe. For instance, analysis of 14th century English manorial records (Ross n.d.) indicates that the Gamma distribution is a good approximation of cereal yields under non-modern conditions. We are less sure of implications of other assumptions, providing opportunity for further analysis.

Conclusion

> '[The good father] … stores up for himself; he stores up for others. He cares for his assets; he saves for others … he saves for the future … [The good farmer] … fills the maize bin.' (from the Florentine Codex: General History of the Things of New Spain (Bernardino de Sahagún, 1953–1982, 10:1, and 10:42), writings of Aztec wisdom, cited in Hendon 2000, 46)

Prehistoric, risk-sensitive households situated in the temperate zone and harvesting unpredictable, seasonally pulsed crops would likely seek the advantages of insuring their survival by over-production and inter-annual storage of the resulting normal surplus. However, under a situation of density-dependent crowding they may only infrequently have had the opportunity to do so. Malthus casts a long shadow over the benefits of inter-annual storage; macro-level system properties can trump the logic of household-level adaptation.

Realistic, evolutionary accounts of the intensification of agrarian production at the expense of foraging, and the development of centralised agrarian societies at the expense of more egalitarian relationships, require that we thoroughly conceptualise the individual mechanisms and processes thought to be involved. Simple models are essential aids in this effort (see also Angourakis *et al.* 2014; Tushingham and Bettinger 2013). We also seek to demonstrate the importance of combining different types and scales of modelling by focusing on the complementary insights available from behavioural ecology and population ecology, and from analytical and simulation methods. Both add to an appreciation of system dynamics. Importantly, micro-level adaptive processes revealed by behavioural ecology at the household level can set up countervailing dynamics at the macro-level of the coupled natural–human system.

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References

Allan, W. 1965. *The African Husbandman*. Edinburgh: Oliver and Boyd.

Angourakis, A., Santos, J. I., Galán, J. M. and Balbo, A. L. 2014. Food for all: an agent-based model to explore the emergence and implications of cooperation for food storage. *Environmental Archaeology* (in press). doi: 10.1179/1749631414Y.0000000041.

Barton, C. M. 2014. Complexity, social complexity, and modeling. *Journal of Archaeological Method and Theory* **21**, 306–324. doi: 10.1007/s10816–013–9187–2.

Barton, L., Newsome, S. D., Chen, F.-H., Wang, H., Guilderson, T. P. and Bettinger, R. L. 2009. Agricultural origins and the isotopic identity of domestication in northern China. *Proceedings of the National Academy of Sciences USA* **106**(14), 5523–5528.

Bogaard, A., Charles, M., Twiss, K. C., Fairbairn, A., Yalman, N., Filipović, D., Demirergi, G. A., Ertuğ, F., Russell, N. and Henecke, J. 2009. Private pantries and celebrated surplus: storing and sharing food at Neolithic Catalhoyuk, Central Anatolia. *Antiquity* **83**, 649–668.

Bowles, S. 2011. Cultivation of cereals by the first farmers was not more productive than foraging. *Proceedings of the National Academy of Sciences USA* **108**(12), 4760–4765.

Campbell, B. M. S. 2007. Three centuries of English crops yields, 1211–1491. Retrieved 15 October 2012, from http://www.cropyields.ac.uk.

Carmean, K. and Sabloff, J. A. 1996. Political decentralization in the Puuc region, Yucatán, Mexico. *Journal of Anthropological Research* **52**(3), 317–330.

Cashdan, E. (ed.) 1990. *Risk and Uncertainty in Tribal and Peasant Economies*. Boulder, CO: Westview Press.

Charles, M., Pessin, H. and Hald, M. M. 2010. Tolerating change at Late Chalcolithic Tell Brak: responses of an early urban society to an uncertain climate. *Environmental Archaeology* **15**(2), 183–198. doi: 10.1179/146141010X12640787648892.

Cohen, M. N. 2009. Introduction: rethinking the origins of agriculture. *Current Anthropology* **50**(5), 591–595.
Earle, T. K. and D'altroy, T. N. 1982. Storage facilities and state finance in the Upper Mantaro Valley, Peru, pp. 265–290 in Ericson, J. E. and Earle, T. K. (eds.), *Contexts for Prehistoric Exchange*. New York: Academic Press.
Ferrari, S. and Cribari-Neto, F. 2004. Beta regression for modelling rates and proportions. *Journal of Applied Statistics* **31**(7), 799–815.
Garfinkel, Y., Ben-Shlomo, D. and Kuperman, T. 2009. Large-scale storage of grain surplus in the sixth millennium BC: the silos of Tel Tsaf. *Antiquity* **83**, 309–325.
Goring-Morris, A. N. and Belfer-Cohen, A. 2011. Neolithization processes in the Levant: the outer envelope. *Current Anthropology* **52**(S4, The origins of agriculture: New data, new ideas), S195–S208.
Hald, M. M. and Charles, M. 2008. Storage of crops during the fourth and third millennia B.C. at the settlement mound of Tell Brak, northeast Syria. *Vegetation History and Archaeobotany* **17**(Suppl. 1), S35–S41. doi: 10.1007/s00334-008-0154-x.
Halstead, P. 1989. The economy has a normal surplus: economic stability and social exchange among early farming communities of Thessaly, Greece, pp. 68–80 in Halstead, P. and O'shea, J. M. (eds.), *Bad Year Economics: Cultural Responses to Risk and Uncertainty*. Cambridge: Cambaridge University Press.
Halstead, P. and O'shea, J. M. (eds.) 1989. *Bad Year Economics: Cultural Responses to Risk and Uncertainty*. Cambridge: Cambridge University Press.
Hayden, B. 1981. Research and development in the stone age: technological transitions among hunter-gatherers. *Current Anthropology* **22**(5), 519–548.
Hendon, J. A. 2000. Having and holding: storage, memory, knowledge, and social relations. *American Anthropologist* **102**(1), 42–53.
Ingold, T. 1983. The significance of storage in hunting societies. *Man* **18**(3), 553–571.
Kirch, P. V., Asner, G., Chadwick, O. A., Field, J., Ladefoged, T., Lee, C., Puleston, C. and Tuljapurkar, S. 2012. Building and testing models of long-term agricultural intensification and population dynamics: a case study from the Leeward Kohala Field System, Hawaii. *Ecological Modelling* **227**, 18–28.
Kohler, T. A. and van der Leeuw, S. E. 2007. Introduction: historical socionatural systems and models, pp. 1–12 in Kohler, T. A. and van der Leeuw, S. E. (eds.), *The Model-Based Archaeology of Socionatural Systems*. Santa Fe, NM: School for Advanced Research Press.
Kuijt, I. 2008. Demography and storage systems during the southern Levantine Neolithic demographic transition, pp. 287–313 in Bocquet-Appel, J.-P. and Bar-Yosef, O. (eds.), *The Neolithic Demographic Transition and Its Consequences*. Dordrecht, he Netherlands: Springer Science+Business Media B. V.
Kuijt, I. 2009. What do we really know about food storage, surplus, and feasting in preagricultural communities? *Current Anthropology* **50**(5), 641–644.
Kuijt, I. and Finlayson, B. 2009. Evidence for food storage and predomestication granaries 11,000 years ago in the Jordan Valley. *Proceedings of the National Academy of Sciences USA* **106**(27), 10966–10970.
Lake, M. W. 2014. Trends in archaeological simulation. *Journal of Archaeological Method and Theory* **21**, 258–287. doi: 10.1007/s10816–013–9188–1.
Lee, C. T., Puleston, C. and Tuljapurkar, S. 2009. Population and prehistory III: food-dependent demography in variable environments. *Theoretical Population Biology* **76**(3), 179–188.
Lee, C. T. and Tuljapurkar, S. 2008. Population and prehistory I: food-dependent population growth in constant environments. *Theoretical Population Biology* **73**, 473–482.
Lee, C. T., Tuljapurkar, S. and Vitousek, P. M. 2006. Risky business: temporal and spatial variation in preindustrial dryland agriculture. *Human Ecology* **36**(6), 739–763.
Leslie, P. W. and Winterhalder, B. 2002. Demographic consequences of unpredictability in fertility outcomes. *American Journal of Human Biology* **14**, 168–183.
Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E. F., Pell, A. N. Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H. and Taylor, W. W. 2007. Complexity of coupled human and natural systems. *Science* **317**, 1513–1516.
McConnell, W. J., Millington, J. D. A., Reo, N. J., Alberti, M., Asbjornsen, H., Baker, L. A., Brozović, N., Drinkwater, L. E., Drzyzga, S. A., Fragoso, J., Holland, D. S., Jantz, C. A., Kohler, T. A., Maschner, H. D. G., Monticino, M., Podestá, G., Pontius Jr., R. G., Redman, C. L., Sailor, D., Urquhart, G. and Liu, J. 2011. Research on coupled human and natural systems (CHANS): Approach, challenges, and strategies (Meeting Reports). *Bulletin of the Ecological Society of America (Reports)* 218–228.
McCorriston, J. and Hole, F. 1991. The ecology of seasonal stress and the origins of agriculture in the Near East. *American Anthropologist* **93**, 46–69.
McPeak, J. G., Lee, D. R. and Barrett, C. B. 2006. Introduction: the dynamics of coupled human and natural systems. *Environment and Development Economics* **11**, 9–13.
Prentiss, A. M., Cail, H. S. and Smith, L. M. 2014. At the Malthusian ceiling: subsistence and inequality at Bridge River, British Columbia. *Journal of Anthropological Archaeology* **33**, 34–48.
Puleston, C. and Tuljapurkar, S. 2008. Population and prehistory II: space-limited human populations in constant environments. *Theoretical Population Biology* **74**, 147–160.
Puleston, C., Tuljapurkar, S. and Winterhalder, B. 2014. The invisible cliff: abrupt imposition of Malthusian equilibrium in a natural-fertility, agrarian society. *PLOS One* **9**(1), 1–13.
Puleston, D. E. 1971. An experimental approach to the function of Classic Maya chultuns. *American Antiquity* **36**(3), 322–335.
Schibler, J. and Jacomet, S. 2010. Short climatic fluctuations and their impact on human economies and societies: the potential of the Neolithic lake shore settlements in the Alpine foreland. *Environmental Archaeology* **15**(2), 173–182. doi: 10.1179/146141010X12640787648856.
Schulting, R. 2010. Holocene environmental change and the Mesolithic-Neolithic transition in north-west Europe: revisiting two models. *Environmental Archaeology* **15**(2), 160–172. doi: 10.1179/146141010X12640787648586.
Smith, B. D. 2001. Low-level food production. *Journal of Archaeological Research* **9**, 1–43.
Smith, D. and Kenward, H. K. 2011. Roman grain pests in Britain: implications for grain supply and agricultural production. *Britannia* **42**, 243–262. doi: 10.1017/S0068113X11000031.
Smith, D. and Kenward, H. K. 2012. 'Well, Sextus, what can we do with this?' The disposal and use of insect-infested grain in Roman Britain. *Environmental Archaeology* **17**(2), 141–150. doi: 10.1179/1461410312Z.00000000012.
Smyth, M. P. 1989. Domestic storage behavior in Mesoamerica: an ethnoarchaeological approach. *Archaeological Method and Theory* **1**, 89–138.
Testart, A. 1982. The significance of food storage among hunter-gatherers: residence patterns, population densities, and social inequalities. *Current Anthropology* **23**(5), 523–537.
Tushingham, S. and Bettinger, R. L. 2013. Why foragers choose acorns before salmon: storage, mobility, and risk in aboriginal California. *Journal of Anthropological Archaeology* **32**, 527–537.
Wesson, C. B. 1999. Chiefly power and food storage in southeastern North America. *World Archaeology* **31**(1), 145–164.
Winterhalder, B. 1990. Open field, common pot: harvest variability and risk avoidance in agricultural and foraging societies, pp. 67–87 in Cashdan, E. A. (ed.), *Risk and Uncertainty in Tribal and Peasant Economies*. Boulder, CO: Westview Press.
Winterhalder, B. 2002. Models, pp. 201–223 in Hart, J. P. and Terrell, J. E. (eds.), *Darwin and Archaeology: A Handbook of Key Concepts*. Westport, Connecticut: Bergin and Garvey.
Winterhalder, B. and Leslie, P. W. 2002. Risk-sensitive fertility: the variance compensation hypothesis. *Evolution and Human Behavior* **23**, 59–82.
Woodburn, J. 1982. Egalitarian societies. *Man* **17**, 431–451.
Wright, H. T. 1984. Prestate political formations, pp. 41–77 in Earle, (ed.), *On the Evolution of Complex Societies: Essay in Honor of Harry Hoijer, 1982*. Malibu, CA: Undena Publications.