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

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Abstract

Using complementary behavioral 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 (e.g., seed requirements, 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 behavioral and population ecological modeling methods has broad and complementary potential for illustrating the dynamic properties of complex, coupled human-natural systems.

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 behavioral 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.

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 centralization (Angourakis, Santos, Galán, and Balbo, 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 an emerging but non-producing political hierarchy, as well as notions of private property and exploitation. However, because current evidence suggests that the productivity of early agriculture was lower than that of foraging (Bowles, 2011), surplus has proven difficult to explain. 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 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 sedentarisim, *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, Cail, and Smith, 2014), the Yucatán (Carmean and Sabloff, 1996), Mesoamerica in general (Smyth, 1989), southwest Iran (Wright, 1984), northern China (L. Barton et al., 2009), and the Levant (Garfinkel, Ben-Shlomo, and Kuperman, 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 specialized 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, that is stored foodstuffs that outlast the harvest cycle.

We define *surplus* as production above annual household requirements, adjusted for expected shortfalls. Our definition formalizes the observation by Allan (1965 : 38) 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.

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.

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* (VCH). 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 labor 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-minimizing tactic is to avoid the dramatic negative consequences of falling short of needs by accepting the 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.

Figure 1a (see also Table 1) presents an array of Beta distributions representing the probability of 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 $\mu = 0.71$ or low $\mu = 0.29$ end of the potential range. For example, if the Beta mean is $\mu = 0.71$, 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 off-set expected average losses, p_e; see Table 1).

[Table 1 near here]

[Figure 1a near here]

Figure 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 formalizes 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 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.

[Figure 1b near here]

Figure 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 1, μ). The optimal investment strategy under a given outcome distribution lies on the rightward-tending ridge that begins with baseline family needs, ideal conditions 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 over-planting.

[Figure 1c near here]

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 Figure 1c (see also Table 1) 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 $\mu = 0.71$, 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 1, 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 and somewhat different but complementary modeling approach based in population ecology and simulation.

This model tracks interactions among an age-structured population, environmental parameters that describe agricultural yields and translate age-specific labor into agrarian production, age-specific consumption requirements of this subsistence population and, finally, functions that translate food availability, conceptualized as a *food ratio* E – kcals available divided by those needed to sustain fertility and mortality at optimal rates – into age-specific survival and fertility. Model parameters are set to values believed to be representative of prehistoric agrarian peoples (Lee, Tuljapurkar, and Vitousek, 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, idealized 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, Puleston, and Tuljapurkar, 2009; Lee and Tuljapurkar, 2008; C. Puleston and Tuljapurkar, 2008; C. Puleston, Tuljapurkar, and Winterhalder, 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 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 conceptualize 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 two-years from the date of its harvest, the cut-off being a simple way of allowing for loss from pilfering, spoilage, and vermin (D. E. Puleston, 1971; D. Smith and Kenward, 2012; D. Smith and Kenward, 2011). A longer shelf life or a more complicated manner of representing the fate of stored foodstuffs are both possible, but we believe they would not change the basic results we present here.

Table 2 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 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 3.82×10^6 kcal/day, or approximately 22% of the typical production on 1000 ha in the CV = 0.3 environment without a storage regime.

[Table 2 near here]

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 to 12,142), but it does not perceptibly change average population welfare measures (Frac $E \geq 1$, life span e_0, or death rate; definitions in Table 2 note). Inter-annual storage available as carry-over to fill the granaries averages 5.43×10^7 kcal, or approximately enough to supply all of the calorie needs of 68 people for a year at a rate of 2200 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%. 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 1.86 x 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 to 0.71).

The sharp drop in average population size with set-asides is expected, as the diverted kilocalories would otherwise support the producing population (C. 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 labor 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 2). 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 6.11 x 10^8 to 1.46 x 10^9. Life span has increased modestly; average death rate remains the same. The variability in both has increased.

Figure 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 (panel a), along with population mortality with storage (b) and without (c) storage, the amount of food (kcals) held in storage (d), and the food ratio

E_t (e) and population size N_t (f) 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 (2f). In general, storage appears to have little effect on the population trajectory at CV = 0.2. This reinforces our reading of Table 2; at this low degree of variation, storage is of limited but not negligible consequence for average population size and welfare outcomes.

[Figure 2 near here]

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 (Figure 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 (panel a) in which $E < 1$ (panel e), leaving the granaries empty or nearly so (panel d) 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 3 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.

[Table 3 near here]

In Figure 3 we illustrate a similar time series with yield CV = 0.3. Yield variance is greater (panel a), as are spikes of famine-induced mortality (panels b and c). Granaries are fuller, more of the time (panel d). 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 (panel e) but average population is lower (panel f). The size of the food-storing population is significantly elevated over its non-storing alternative, especially after the famine in year 130. All of these trends are consistent with the averaged results of ten simulations presented in Table 2 (CV = 0.3; 40% set-aside).

[Figure 3 near here]

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 4). 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 (panel f).

[Table 4 near here]

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 labor 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. Of course, average population 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 Figure 2d; Table 2, Frac $E \geq 1$].

Discussion

Through complementary modeling 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, Lee, and Barrett, 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, Pessin, and Hald, 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 (B. D. 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 been conceptualized and defended by its producers or how some portion of 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 (Figure 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 2) – 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. But, unless other staples are making a significant contribution to diet, 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 carryover. Even if baseline requirements for stored food are known, the highly skewed distribution of storage volumes arising from our simulations (Figure 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 (Figure 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 2; Figures 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 $E \geq 1$, 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 4). 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, household behavior, 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 (D. Smith and Kenward, 2011: 257). The potential interactions are more complex than have been recognized, 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 (C. M. Barton, 2014: 311). We rely on assumptions basic to the risk-sensitive (Leslie and Winterhalder, 2002; Winterhalder and Leslie, 2002) and food-limited approaches (C. Puleston and Tuljapurkar, 2008; C. Puleston et al., 2014) that inform our analyses. We make several additional, important simplifying assumptions. We model yield fluctuations through independent random draws from Gamma distributions (Figure 1a), a procedure which homogenizes the spatial dimension of the agricultural environment and eliminates the possibility of temporal auto-correlation among environmental states. We assume a singular, idealized household type, meaning our model does not recognize variation in household consumption requirements, labor availability, skill or access to productive resources. We provide our households choice over only one agro-economic option for avoiding production risk, their TIP or target input package, modeled 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. And, in our population ecology simulations, 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 some 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 of the 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 centralized agrarian societies at the expense of more egalitarian relationships, require that we thoroughly conceptualize the individual mechanisms and processes thought to be involved. Simple models are essential aids in this effort (see also Angourakis et al., 2014). We also seek to demonstrate the importance of combining different types and scales of modeling by focusing on the complementary analytical insights available from behavioral 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 behavioral ecology at the household level can set up countervailing dynamics at the macro-level of the coupled natural human system.

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Tables

Table 1. Beta distribution parameters and properties, and their variance compensation effects.

Beta Parameters and Properties				Variance Compensation				
α	β	Mean μ	Disper-son ϕ	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 Figure 1a. α and β are the shape parameters for a Beta distribution, reparameterized 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.

Table 2. Population and welfare effects of fixed cost set-asides and storage.

Set-aside	Storage	$\bar{E}$	$\bar{N}$	Frac $E \geq 1$	e_0 [yrs]	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)	5.43 x 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)	1.86 x 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)	6.11 x 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)	1.46 x 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/yr] gives the average inter-annual holdings in the granaries. One run from the ten (40% set-aside scenario) is shown as a 300-year time-path in Figure 2 (CV = 0.2) and one in Figure 3 (CV = 0.3).

Table 3. 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 Figure 2.

Table 4. 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 Figure 3.

Supplemental Materials

Variance Compensation: We assume that under ideal conditions an input package generates a maximum of one target output unit, and under the worst conditions it generates zero output units. The value of any particular output unit is modeled as a stochastic realization from a Beta distribution using the *stats* package in R. The Beta distribution is usually parameterized with two positive real shape parameters, α and β. To obtain a more useful modeling structure (Ferrari and Cribari-Neto, 2004), we reparameterize the distribution in terms of a mean parameter, μ, and a dispersion parameter, ϕ (see Table 1, Main Text):

$$\mu = \frac{\alpha}{\alpha+\beta} \text{and } \phi = \alpha + \beta.$$

We simulate a matrix, $\boldsymbol{\theta}$, of output units from a given number of input units, $j_{=1,2,..2000}$, under a series of Beta distributions indexed by $i_{=1,2...100}$:

$$\boldsymbol{\theta}_{[i,j]} = \sum_{r=1}^{j} \mathrm{B}_r\left(\alpha_{[i]}, \beta_{[i]}\right),$$

where $\mathrm{B}_r\left(\alpha_{[i]}, \beta_{[i]}\right)$ is the r^{th} realization from a Beta distribution with parameters: $\alpha_{[i]} = \mu_{[i]}\phi$, $\beta_{[i]} = (1-\mu_{[i]})\phi$, and $\phi = 13.4$ is a constant value determined empirically from wheat yields in preindustrial England, 1280-1400 (Campbell, 2007). The agrarian environment becomes increasingly hostile as $\mu_{[i]}$ decreases in the open interval (0,1). We then calculate the matrix of fitness/utility values, $\boldsymbol{\Phi}$, by passing each element of $\boldsymbol{\theta}$ through the value function (Figure 2, Main Text):

$$\boldsymbol{\Phi}_{[i,j]} = e^{\left(\frac{M^2}{(M-N)^2} - \frac{M\boldsymbol{\theta}_{[i,j]}}{(M-N)^2}\right)} \boldsymbol{\theta}_{[i,j]}^{\left(\frac{M^2}{(M-N)^2}\right)} M^{-\left(\frac{M^2}{(M-N)^2}\right)},$$

where: $M = 700$ output units defines the outcome in which fitness/utility reaches its maximum, and $N = 200$ is a dispersion parameter. We plot the fitness isocline map using the *contour* function in R.

Population Ecology: For analysis of the population-level consequences of storage and taxation we adapt the methods of food-limited demography described in Lee and Tuljapurkar (2008), Puleston and Tuljapurkar (2008), Lee *et al*. (2009), and Puleston *et al*. (2014). Demographic properties of an age-structured population are represented by Leslie matrices in the MatLab software environment. Empirically-based relationships between per capita food availability, and age-specific survival and reproduction determine population growth or decline. Parameterization for prehistoric population conditions is discussed in Lee *et al*. (2006) and Lee and Tuljapurkar (2008), and an analytical approximation of the dependence of food availability on the parameters in a variable environment is discussed in Lee *et al*. (2009). We use the parameters employed in these publications unless otherwise specified.

Food production is determined by environmental factors, competition and labor availability. In the present simulations, yield is determined by independent draws from a near-symmetrical Gamma distribution not significantly different from normal and with a realistic mean productivity per hectare. Food generated on 1000 arable ha is assumed to be distributed proportional to age-specific needs.

Fixed set-asides are conceptualized as removing food from the simulation, making it unavailable to the producers. Storage is modeled by assuming that all food availability in excess of baseline need to optimize survival and reproduction is set-aside on an annual basis and is added to the production of the next year (see text for specifics). The oldest (stored) food is assumed to be eaten first and no food can be stored for more than two years.

<u>Distributions</u>: Our first model uses a Beta distribution because we are investigating unit-level outcomes, each supported on the unit interval (0,1); our second model uses a Gamma distribution because we are pooling (summing) a large number of unit-level outcomes across a large number of households, such that each outcome needs support on the positive reals $(0,\infty)$.Each distribution is thus suited to the domain being modeled. Although the Gamma and Beta appear to have different properties, the sum of n random Beta variables approaches a Gaussian distribution as n grows large. Likewise, a Gamma distribution approaches a Gaussian distribution as the shape parameter grows large relative to the scale parameter. In both of our models, the distributions utilized are approximately Gaussian, with the constraint that negative values of crop yields are not possible.

Figure Captions

Figure 1. (a) Risk-sensitive, variance compensation for seasonally pulsed, agrarian yields. (a) Beta densities declining from $\mu = 0.91$, to $\mu = 0.09$, 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 realized output. The asymmetric shape of this function formalizes 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 an input package target production (x-axis), the value function, and increasing environmental challenge (y-axis), as modeled 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 1 for values.

Figure 2. Time series of environmental variation and population response (CV=0.2). Panel (a) gives Gamma distribution, yield variation, (mean = 21,000kcal/ha/day, CV = 0.2); panels (b) and (c) show hunger-induced 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 (gray) and no-storage (black) scenarios. Discussion in the text.

Figure 3. Time series of environmental variation and population response (CV=0.3). Panels defined as in Figure 2.

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 meet 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 Figures 2 and 3 for the time series from which these results were drawn.

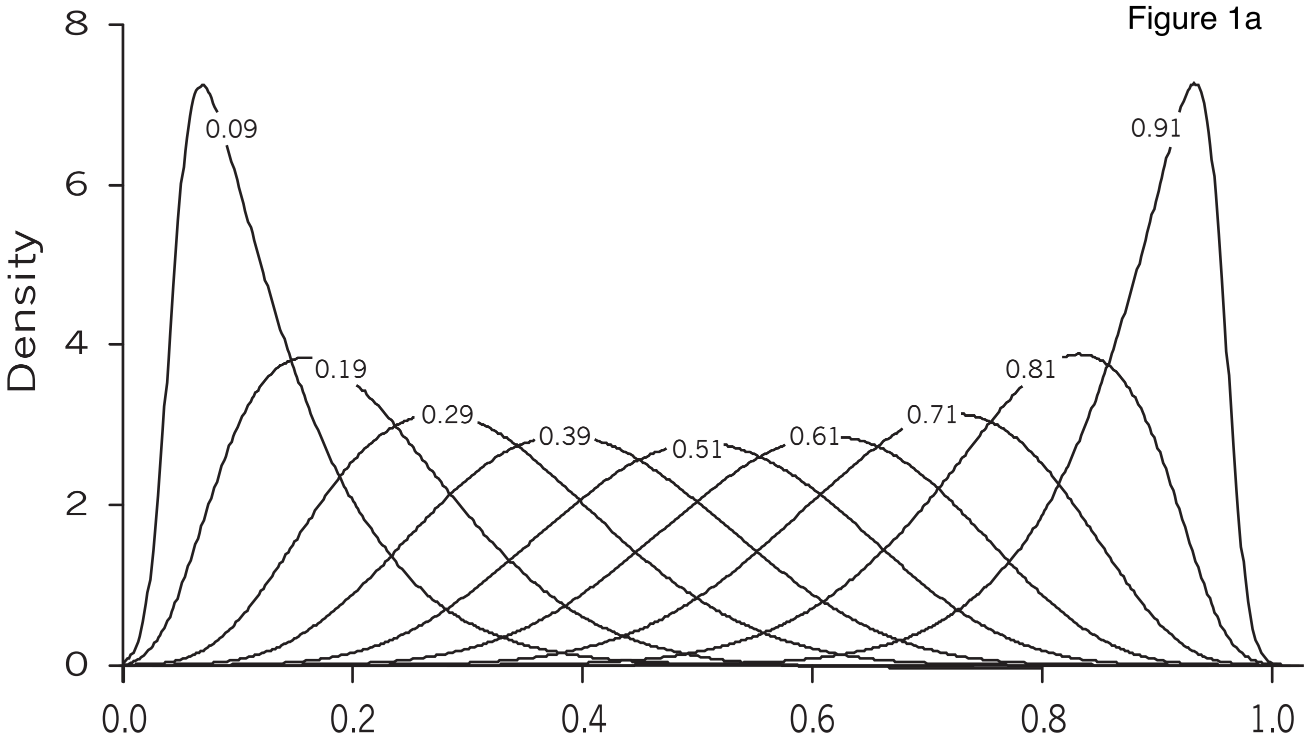


Figure 1a
Density
8
6
4
2
0
0.0
0.2
0.4
0.6
0.8
1.0
0.09
0.19
0.29
0.39
0.51
0.61
0.71
0.81
0.91

Figure 1b

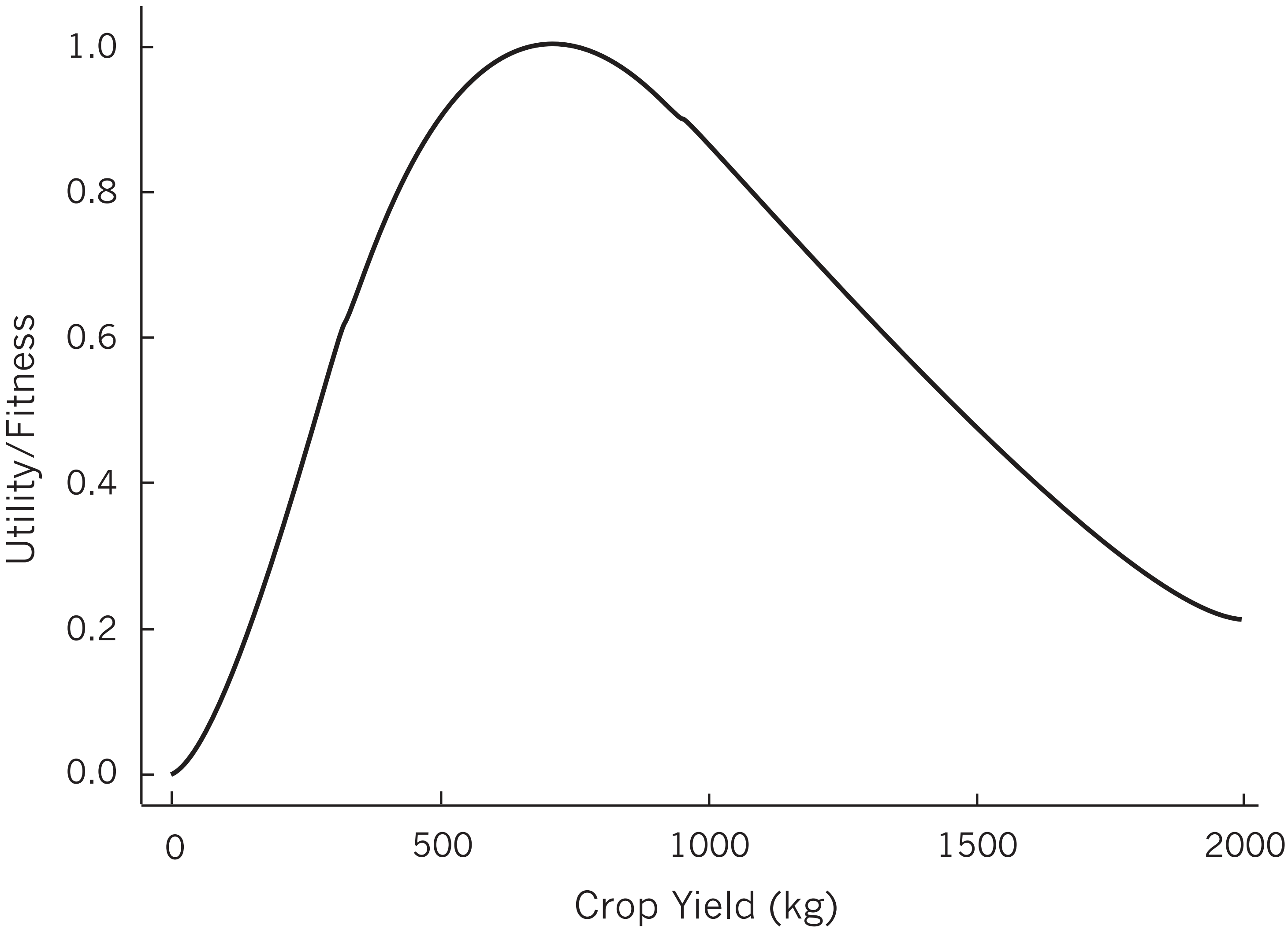
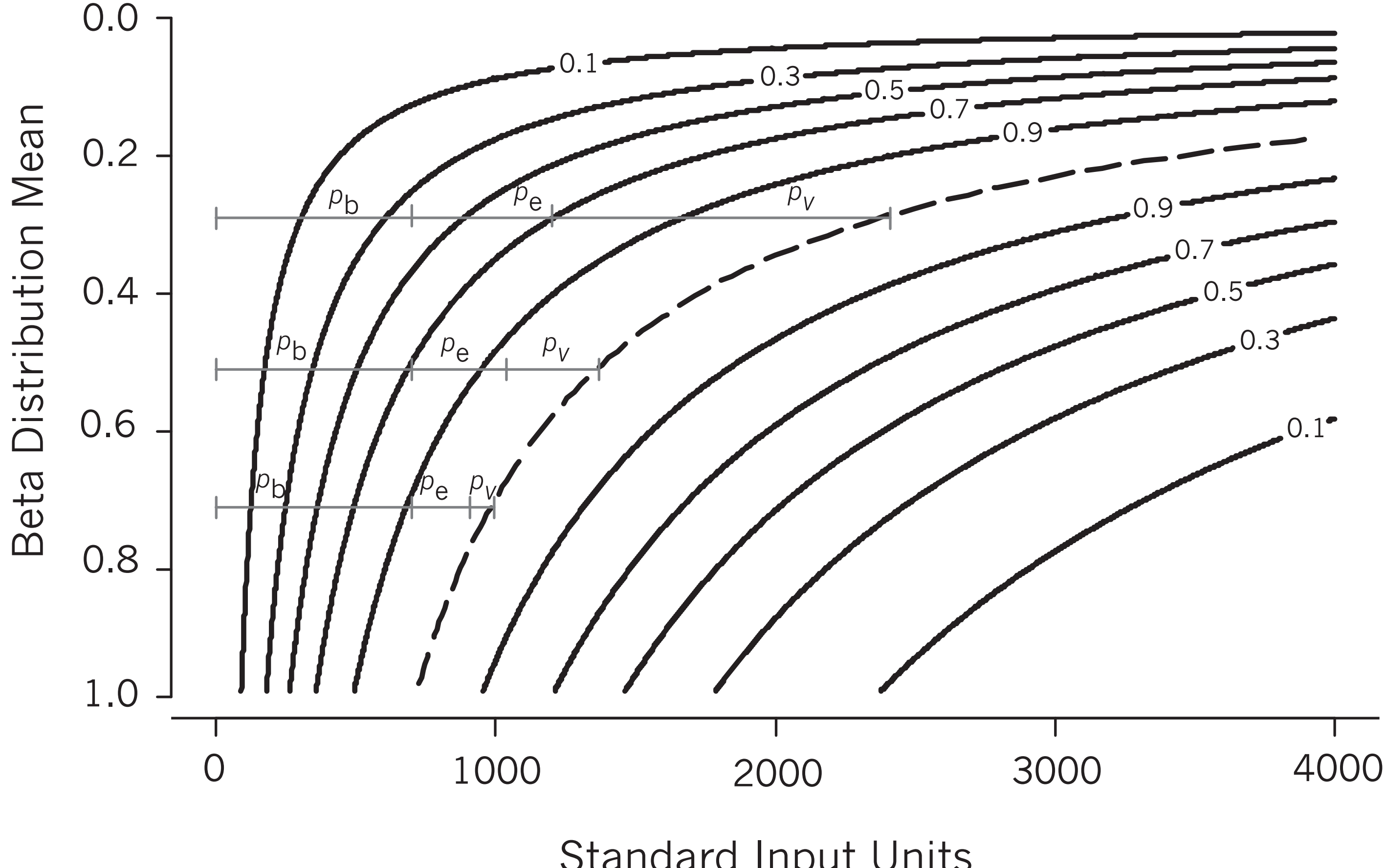
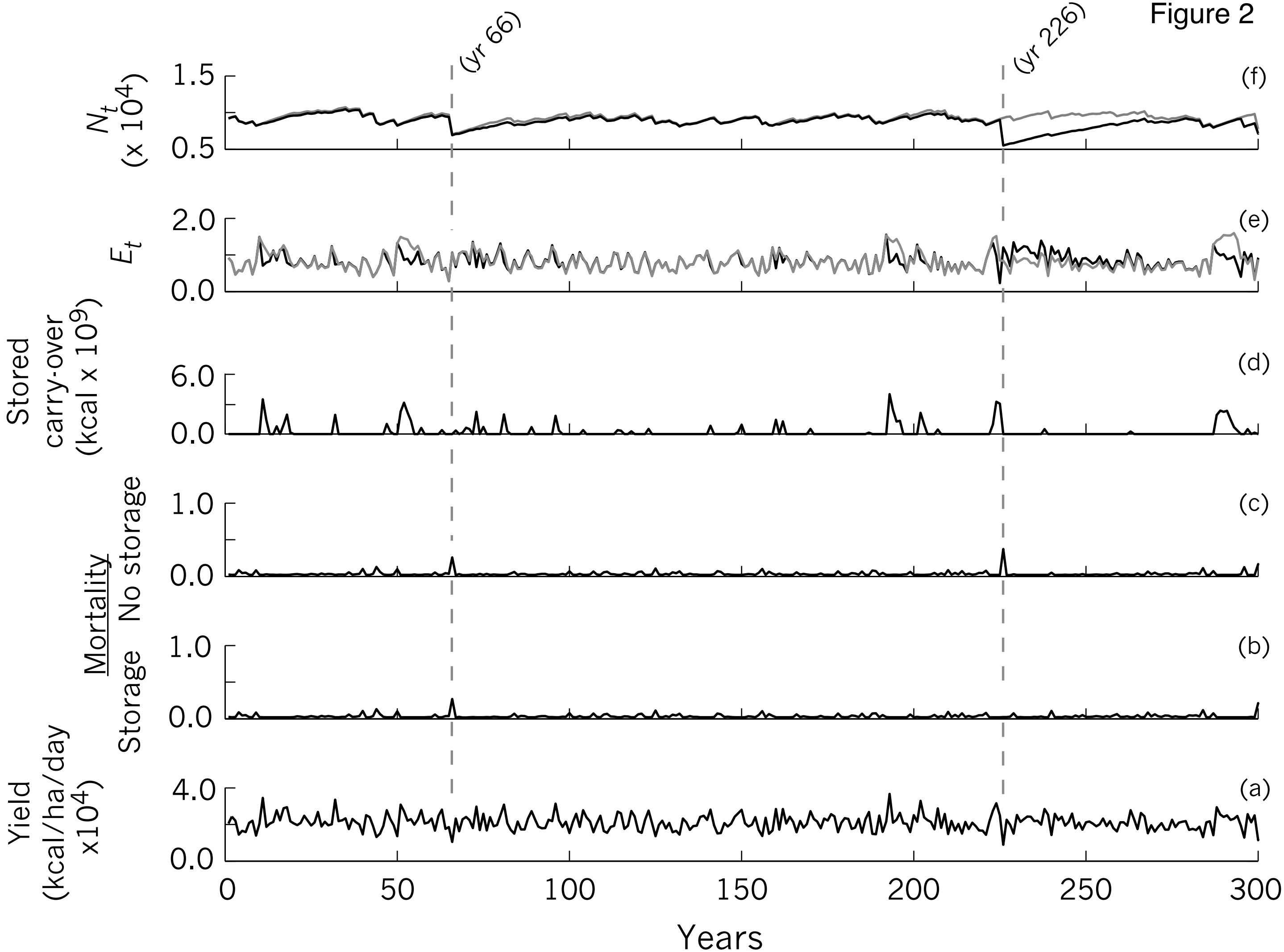

1.0
0.8
0.6
0.4
0.2
0.0
Utility/Fitness
0
500
1000
1500
2000
Crop Yield (kg)

Figure 1c



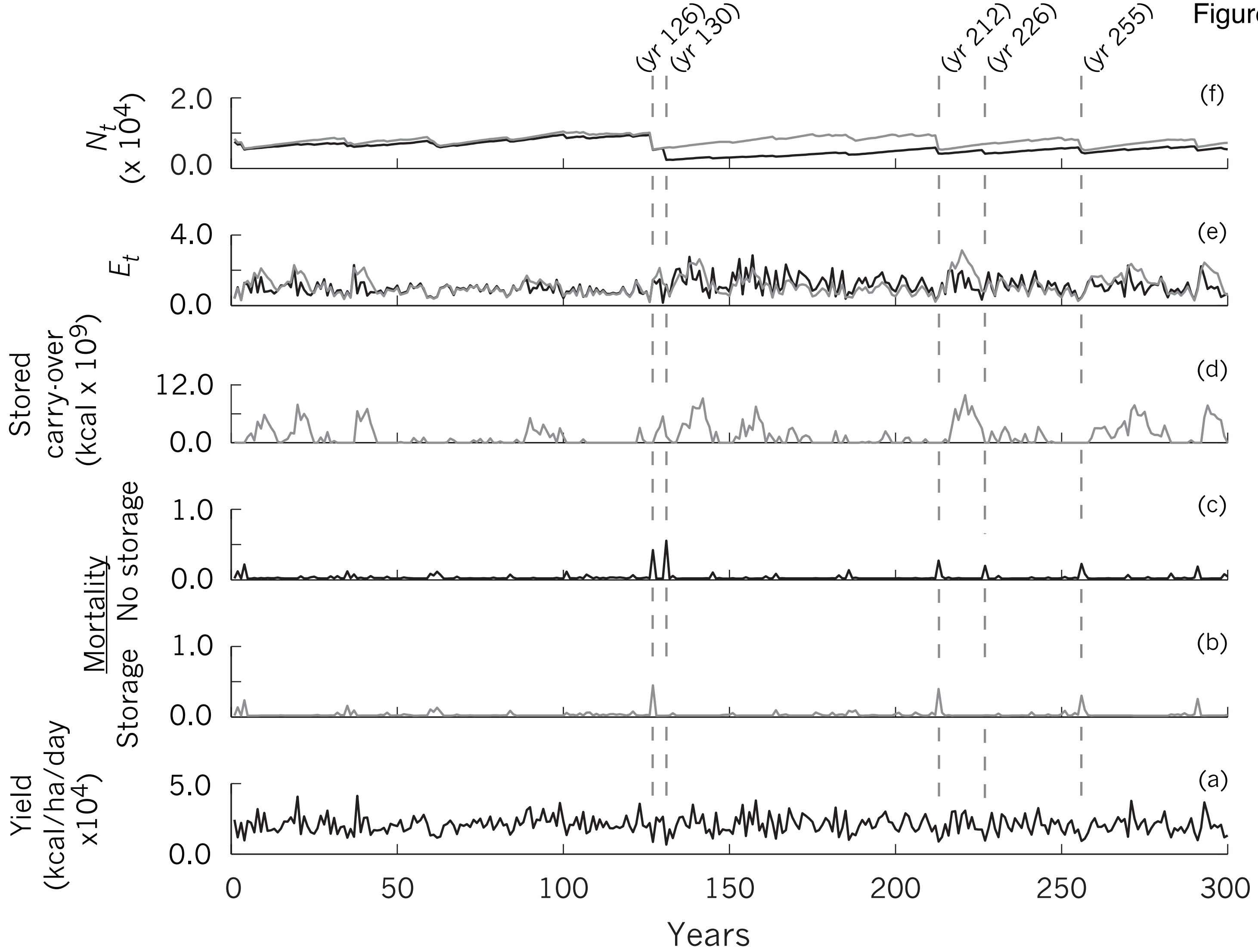
Beta Distribution Mean
0.0
0.2
0.4
0.6
0.8
1.0
0.1
0.3
0.5
0.7
0.9
0.9
0.7
0.5
0.3
0.1
p_b
p_e
p_v
p_b
p_e
p_v
p_b
p_e
p_v
0
1000
2000
3000
4000
Standard Input Units

Figure 2



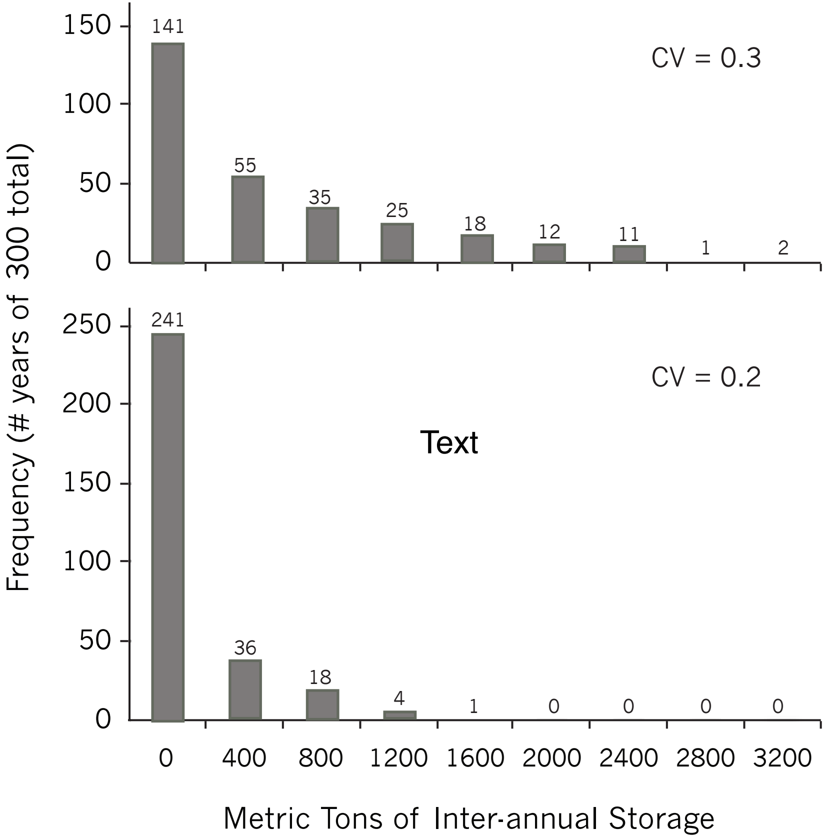
(yr 66)
(yr 226)
(f)
N_t (x 10^4)
1.5
0.5
(e)
E_t
2.0
0.0
(d)
Stored carry-over (kcal x 10^9)
6.0
0.0
(c)
Mortality
No storage
1.0
0.0
(b)
Storage
1.0
0.0
(a)
Yield (kcal/ha/day x10^4)
4.0
0.0
0
50
100
150
200
250
300
Years

Figure 3



(yr 126)
(yr 130)
(yr 212)
(yr 226)
(yr 255)
N_t (x 10^4)
2.0
0.0
(f)
E_t
4.0
0.0
(e)
Stored carry-over (kcal x 10^9)
12.0
0.0
(d)
Mortality
No storage
1.0
0.0
(c)
Storage
1.0
0.0
(b)
Yield (kcal/ha/day x10^4)
5.0
0.0
(a)
0
50
100
150
200
250
300
Years

Figure 4



Frequency (# years of 300 total)
150
100
50
0
141
55
35
25
18
12
11
1
2
CV = 0.3
250
200
150
100
50
0
241
36
18
4
1
0
0
0
0
CV = 0.2
Text
0
400
800
1200
1600
2000
2400
2800
3200
Metric Tons of Inter-annual Storage