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Risk-sensitive fertility
The variance compensation hypothesis

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Abstract

Two conditions are sufficient to indicate the need for risk-sensitive, adaptive analysis: (i) the outcomes of a behavior must be unpredictable to some degree and (ii) the relationship between outcomes and their value (in terms of fitness or utility) must be nonlinear. We argue that these conditions are common, and develop a general model for the analysis of risk-sensitive fertility behavior when long-term reproductive outcomes are unpredictable. We show that unpredictability is likely to have a patterned effect on fertility behavior, beyond adjustment for expected or average mortality, and we analyze the conditions under which that effect will be to promote or dampen fertility (positive or negative variance compensation, respectively). We then describe the implications of this variance compensation hypothesis (VCH) for the analysis of demographic transitions, agricultural intensification, fertility differences in natural-fertility populations, and clutch size. We conclude by lamenting that data are lacking to test the VCH, probably because it has not been appreciated that there can be patterned and effective behavioral adjustments to stochastic features of the environment.

Keywords: Human behavioral ecology; Risk; Risk-sensitive adaptation; Fertility; Reproductive behavior; Agricultural intensification; Demographic transitions; Boserup; Clutch size; Lack hypothesis

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1. Introduction

In this paper, we explore the demographic consequences of the following premise: the long-term outcome of bearing a child is unpredictable to some degree. Due to stochastic factors affecting pre-adult mortality, parents cannot predict from the number of children they bear their completed family size as they near the end of their reproductive years. In effect, long-term fertility outcomes are probabilistic. The premise itself is unexceptional, but it appears both to have been neglected in the literature (Cain, 1983 is an exception) and to have quite interesting implications. To show how this is the case, we describe and illustrate a conceptual model of risk-sensitive adaptive behavior. We then modify this model to fit the specific case of long-term fertility outcomes. We propose that this model may be relevant to some of the more vexing issues of historical demography, such as demographic transitions and Boserup's (1965, 1981) claim that population pressure impels agricultural intensification. In biological terms, the unpredictability of reproductive outcomes may help us to better understand clutch- or litter-size (the Lack model).

To establish in colloquial terms the analytical context and problem, consider this ethnographic scenario. A young couple has married. They are living with the husband's parents, anticipating a long wait to set up their own household. The subsistence regime is one of short-fallow, peasant agriculture. The couple is initiating the economic and reproductive behaviors that will shape their lives over a family cycle. As a consequence of diverse socioecological conditions — land holding and tenure, social practices related to marriage and inheritance, labor requirements of the cropping regime — their optimal completed family size is four grown children, but in no case dare they chance ending their reproductive years with fewer than three adult offspring. The potential negative consequences of falling short are many. The couple might suffer from inadequate support in old age. The family's agricultural holdings might be threatened. Their too few offspring might find marriage — hence, reproductive success and genealogical continuity — difficult or impossible without the support and possibly the social exchange value of siblings of the appropriate age and sex. In contrast, the negative effects (the costs) of exceeding their optimal complement of grown children, while real, are not nearly so dramatic. They might entail, for instance, a modest decline in net per capita agricultural production from family holdings.

If the long-term outcome of this new couple's planning were entirely predictable, they would need only to make astute economic choices to support the birth and rearing of four offspring, the optimum. If they knew with assurance that some fraction of children born would die before adulthood, they could adjust accordingly. In this deterministic version of our scenario the world is governed by well-behaved constants; goal-directed, adaptive behavior is relatively straightforward. However, if the long-term outcome of four or more births is largely unpredictable, so that the number of children surviving to adulthood is a distribution with significant variance, then in order to avoid the catastrophe of two or fewer adult offspring the couple may find themselves constrained to aim for five, six, or perhaps more children. They must plan an excess, and hazard the modest cost of a greater than optimal number surviving, in order to minimize the chance of a disastrous shortfall. Stochasticity itself will affect their best-choice reproductive tactic quite apart from average

outcomes and predictable losses. This is the type of situation we seek to examine, and which we claim may have broad demographic implications.

2. Conceptual elements of a risk-sensitive analysis

Such stochasticity constitutes risk in the economic sense of unpredictable variability in an outcome. Risk can act independently of average outcomes in the structuring of adaptation. Two conditions jointly are sufficient to indicate need for a risk-sensitive analysis of adaptive behavior: (a) the relationship between possible outcomes and the values assigned them must be nonlinear over some portion of its range; and (b) those outcomes, the adaptively meaningful consequences of the behaviors being considered, must be unpredictable to some degree. That is, any choice or action must give rise to two or more possible results, each with clear odds but without assurance of occurring. Examples might include energy capture rates that follow from a particular subsistence choice by hunter–gatherers or the range of possible completed family sizes that follows from a particular reproductive tactic early in the family cycle. Both of the required conditions — nonlinear valuation and unpredictable outcomes — probably are met more commonly than has been appreciated. While the conceptual apparatus for analyzing risk-sensitive choices is fairly straightforward, it rarely has been employed [for instance, in the large anthropological literature on subsistence risk (Winterhalder, Lu, & Tucker, 1999)]. We know of no examples in which it has been applied directly in studies of demography.

In general, we adopt a behavioral ecology approach derived from neo-Darwinian theory (Winterhalder & Smith, 2000). The assumptions and methodological commitments of this orientation overlap significantly with the field of family economics (review in Robinson, 1997). However, this signaling of theoretical orientation should not obscure our conviction that some of the problems we address — e.g., human fertility behavior — are multidisciplinary by their nature (Caldwell, Caldwell, & Caldwell, 1987; Greenhalgh, 1990; Kertzer & Fricke, 1997; Siegers, 1990).

2.1. Definitions

Risk is unpredictable variability in the outcome of an adaptively significant behavior. This is the standard economic definition of risk and is not to be confused with the colloquial usage that equates risk with peril or degree of hazard. Unpredictable variability may arise because behavioral outcomes are fundamentally stochastic (pure risk). Or, it may arise because the actor lacks accessible information on outcomes (uncertainty), a distinction first proposed by Knight (1921).

Value (V) we use to denote the metric for making relative assessments of outcomes. We adopt this term as a gloss for utility and reproductive fitness, the currencies of greatest importance in economic and evolutionary biology theory, respectively. There are, of course, interesting and difficult questions raised by the relationship of utility to fitness: which to use for human behavior? How they might be combined to make up a joint currency? How they are to be measured? These questions beg attention especially when we focus on fertility.

However, the model we describe does not require a resolution of these issues at this point, and so we define value to subsume whichever metric we might apply to assessing success.

For purposes of hypothesis generation, we assume that humans behave in ways that maximize value (utility, fitness) within constraints (Foley, 1985; Maynard Smith, 1978; Parker & Maynard Smith, 1990). For clarity, we always will describe the relationship between outcome (e.g., calories acquired, fertility achieved) and payoff (e.g., utility, fitness) in terms of a value *function*. We will speak of the relationship between the behavior (resource selection, reproduction) and its consequences (calories acquired, fertility achieved) in terms of an outcome *distribution*. We call the range of behavioral options being considered the *alternative set*. In studies of foraging behavior, this might be the particular array of resource combinations that could be pursued and harvested. In demographic studies, it might be actions early in the family cycle concerning acquisition of resources or the number of births planned for the family.

2.2. Nonlinear value functions

If a value function is linear, then even if the outcomes of a behavioral option are stochastically distributed, the variance (or risk) is immaterial to assessing their relative value. A measure of central tendency (e.g., average value) suffices to rank each of the alternatives. By contrast, if the value function is nonlinear, variance effects must be included in such a ranking. Consider the choice over a two-option alternative set: a fixed reward of x, or a variable reward with equal, 50:50, odds of $x+k$ or $x-k$ (Fig. 1a). The fixed and variable options in this set have the same mean outcome x. However, if the alternatives fall on an accelerating portion of the value function (convex to the x-axis), then the variable reward ($x \pm k$) has the higher expected value and will be preferred. In economic terms, the risk- or variance-prone option is optimal. However, if the alternatives fall on a decelerating or concave portion of the curve, then the fixed reward (x) has the higher value and the optimal choice will be risk- or variance-averse. This simple comparison generalizes to any symmetrical outcome distribution and illustrates the conventional economic wisdom that increasing marginal returns lead to risk-prone behavior. Decreasing marginal returns lead to risk-averse behavior.

For food or other material resources necessary to survival, and more generally for many consumer goods, there are good reasons to presume that the value function is S-shaped or sigmoid in form (Fig. 1a; see Friedman & Savage, 1948). This is no less true for songbirds (Caraco, Martindale, & Whittam, 1980) than for humans. We argue below (Sections 3.1 and 3.2) that a value function somewhat different from the sigmoid may be more appropriate for analysis of reproductive behavior.

2.3. Outcome distributions

For alternative sets related to foraging behavior, it is conventional to use a normal distribution to describe the odds of stochastic outcomes (Stephens & Charnov, 1982). Fertility outcomes, however, are better described by a binomial distribution (Section 3.3 below).

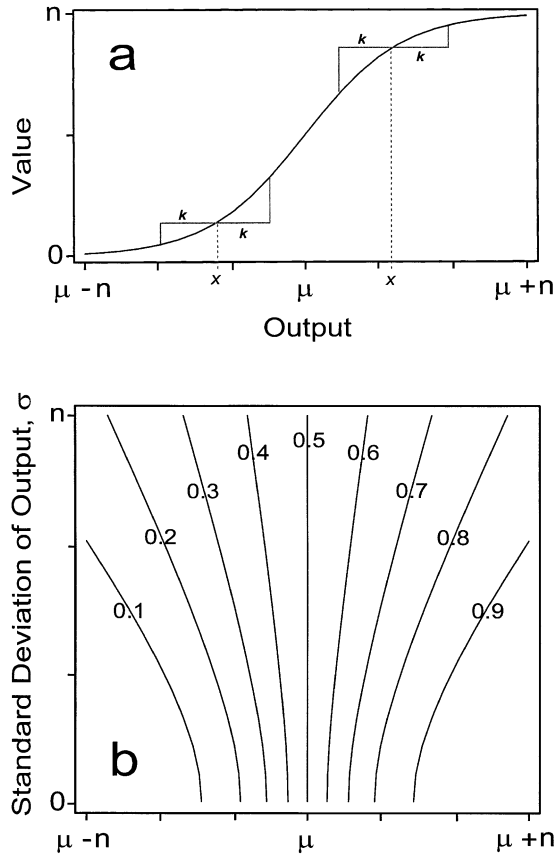

Fig. 1. (a) Sigmoid value function, with respect to foraging output, illustrating the basic logic of risk-sensitive adaptive tactics for subsistence production. If the value function is accelerating, then 50:50 odds choice of $x \pm k$ is preferred over the fixed choice x. If the value function is decelerating, to the right of the inflection point, then the fixed choice x is more valuable than even odds of $x \pm k$. (b) An iso-value map for the sigmoid value function shown in (a) and normal outcome distributions. Value (fitness, utility) is represented on a scale of 0 to 1. Each subsistence alternative gives rise to a normal probability distribution of outcomes (e.g., net acquisition rates). The expected value of that distribution, hence, the desirability of the alternative associated with it, is located via its mean and standard deviation (μ,σ) of output. The set of available alternatives can then be ranked relative to one another by their expected values (Winterhalder et al., 1999).

2.4. Iso-value maps

A value function describes the relationship between an outcome or reward (say net energy yield or number of surviving offspring) and its value. An outcome distribution associates each behavioral option in the alternative set with its outcomes and their odds. These relationships may be continuous or discrete; for the moment, we focus on the continuous possibility for its generality and ease of visualization. Given these two relationships, the expected value of an option in the alternative set is the integral of

the likelihood of each of its possible outcomes multiplied by each outcome's value. We have:

$$E_i[V(x)] = \int V(x) f_i(x) \mathrm{d}x \tag{1}$$

In prose, the expected value of alternative i, $E_i[V(x)]$, is the product of the value function $V(x)$ and the probability distribution $f_i(x)$ specific to alternative i, integrated over each possible outcome (x). The best behavioral option is the alternative having the highest expected value.

The expected values (Eq. (1)) for a particular value function and the full array of possible choices in the alternative set can be conveniently represented as an iso-value map. Each alternative is characterized by an associated normal distribution; it thus is located on this map by its variance (or standard deviation) and mean. The iso-value map in Fig. 1b represents the interaction of a smoothed sigmoid value function (Fig. 1a) and normal outcome distributions. The x-axis of the map (S.D. = 0) simply replicates in a topographic representation the value curve itself. As standard deviation increases, it has the effect of spreading the iso-value lines into a fan-like form, the consequence of finding options increasingly affected by stochasticity. This iso-value map allows us to compare the expected value, hence, relative desirability, of any option in the alternative set via its associated mean and standard deviation of outcome.

With this iso-value map, the reader can verify our earlier observations concerning risk-averse and risk-prone behavior for comparisons among options with and without variance, and with means located in the convex and concave portions of the value function (below or above the inflection point, respectively). In fact, an iso-value map can be used to rank alternative-set options characterized by any combination of means and variances (see Winterhalder et al., 1999).

3. Risk-sensitive analysis of completed fertility

3.1. The value function as a vehicle for socioeconomic conditions

The sigmoid curve adopted in standard analyses of risk summarizes a wide array of bio-psychological factors affecting the consumption of food and other goods. Similarly, it is appropriate to view a fertility value function as the vehicle by which diverse socioenvironmental factors affecting fertility might be brought into an analytical model. These factors potentially include legal or customary restrictions on child labor, the work requirements of agricultural production, the opportunity costs of male and female parenting, the need for secure, cross-generation transfer of land tenure or other subsistence rights, bride-price and other marital customs, or the evolutionary tendency to optimize reproductive success. This range of possibilities raises several considerations in our definition of value.

The first is time frame. We have defined value so that it subsumes utility and/or reproductive success. Both currencies invite a cross-generational focus on the family. Reproductive decisions have consequences — costs and benefits in terms of value — across and beyond the life span of the parents. There is, for instance, the long-term success of the

lineage as a sociological unit able to maintain access to a key requirement of production such as land or herds. There also is its success as a reproductive unit of descending generations. We assume parents act across the cycle of their family unit to best insure their own economic and reproductive success, and those of their children.

Secondly, in the model, we treat this cross-generational time frame as if it were a discrete, two-stage development rather than a continuous process. A couple has a set number of births; an actual outcome (number of adult offspring) then follows according to the binomial odds. The model does not allow parents to compensate for offspring mortality within their reproductive career. This simplification raises interesting questions, which we nonetheless set aside for now.

The third consideration is representation. There are three, interrelated ways of representing a value curve. The *y*-axis variable could be marginal value, average value per child, or total value of all children, as a function of the number of births and survivorship. We will use total value of children, noting that a function for this measure fully specifies the other two possibilities. The units of the *x*-axis are number of offspring born, but they might also represent the resources invested in rearing a child (assuming that all receive equal treatment). The value function then is yield as a function of investment and is analogous to the standard economic production function.

The fourth issue is units. Consistent with our earlier decision to gloss the distinction between utility and reproductive fitness, we do not specifically define the measurement of value. We require only that it be well behaved, to at least the same degree that economists assume for utility. We recognize that the issue of defining and measuring an appropriate currency is a hoary one for empirical use and evaluation of the model.

We add several, further simplifying assumptions. We assume that children are homogeneous with respect to aptitude, costs and potential value (e.g., any birth surviving to adulthood is equivalent). We assume that probability of survival to adulthood (p) — the prime stochastic variable of our model — is constant across children and thus independent of parity, gender, class, etc. With modelers' faith, we believe these departures from reality only increase the chance for creative elaboration later, should the initial and highly simplified approach make that effort appear sufficiently worthwhile.

Finally, diverse kinds of actions or choices might fall within the alternative set of a risk-sensitive fertility model. These certainly would include choices or behaviors directly affecting reproduction (e.g., marriage, coitus, etc.). However, they might also include obtaining the resources, which must be mobilized over a lifetime to insure that births reach favorable adult outcomes. There is no simple, *a priori* way of separating an obviously relevant behavior, such as acquiring a second wife, from a less apparent one: rental of extra fields in the hope of eventually accumulating the wealth needed to attract and support her (Voland, 1995). Either action may be important to risk-sensitive fertility.

3.2. The right-ibis value curve

However assayed, a value distribution over completed family size (number of surviving adult offspring) is unlikely to be linear. In fact, one of the more interesting entailments of this

model is the variety of ways in which environmental, socioeconomic and other conditions might combine to give this function a complex shape, especially for an organism such as humans, whose livelihood depends always on social living and often on long-term capital assets such as land or livestock. To illustrate this claim, we propose a particular form for the fertility value function in a situation of intensive, peasant agricultural production. While we believe this particular form has important generality, we encourage the reader to consider ways in which alternative curves might come about.

The context is a system of small-holder, household-based agricultural production (Netting, 1993), what Cain (1983, p. 692), following Hajnal and others, calls the "joint household system." Typical features are those of our introductory scenario. We postulate that in this context the cumulative value function for fertility will be positively and steeply accelerating (convex) at low completed family size, passing through an inflection point to become negatively accelerated (concave) (Fig. 2a). The curve has an intermediate peak and then falls off gradually with higher than optimum fertility. The number of adult offspring at the peak of this curve (5) is arbitrary; the curve's most important features are its asymmetry and its intermediate maximum. Technically, the value curve is formed from a three-parameter, piecewise-defined function (see Appendix A, Leslie & Winterhalder, 2001).

To justify this form, imagine that a late-cycle couple with only one or a few grown offspring faces the poor prospects described earlier: limited offspring marriage possibilities and tenuous land tenure. This small offspring group likewise may have greater than usual difficulty supporting aged parents. For example, based on studies in South Asia, Cain (1983, p. 691) notes that... "instances of misfortune befalling aging parents who do not have a surviving son to depend on...; insecurity of property rights, widespread failure of financial and insurance markets, and absence of important extrafamilial welfare institutions... point to the salience of parental security concerns for reproductive strategies." Thus, at very low family size, each added sibling substantially improves the long-term value of the offspring group. The value function is positively accelerated. The peak reflects the parental, quantity–quality trade-off between numbers of children and capacity to invest in the development of each of them. It is the most children the couple can support or utilize without putting such a damper on household returns that declining prospects characterize them all (Blurton Jones & Sibly, 1978; Boone & Kessler, 1999; Luttbeg, Borgerhoff Mulder, & Mangel, 2000). With more than the peak number, nutrition and education of the offspring cohort may suffer and inheritance of productive assets may dip below viability for some or all members of the next generation. To the right of the peak, the value function declines relatively slowly because of the potential for agricultural production to respond to labor intensification and absorb the work capacity of extra children. Alternatives such as emigration or sale of household produce to urban markets may also mitigate the burdens of exceeding the ideal family size.

We term this a "right-ibis" value function for its similarity to the right-facing profile of this shore bird, with its long and slightly downward curved beak. It presumes that the socio-ecological circumstances common to peasant agriculture will be more forgiving of too many than too few grown children in the family.

If the parental couple could predict with assurance the outcome of their early reproductive actions, then they would acquire the resources and bear the number of children required to

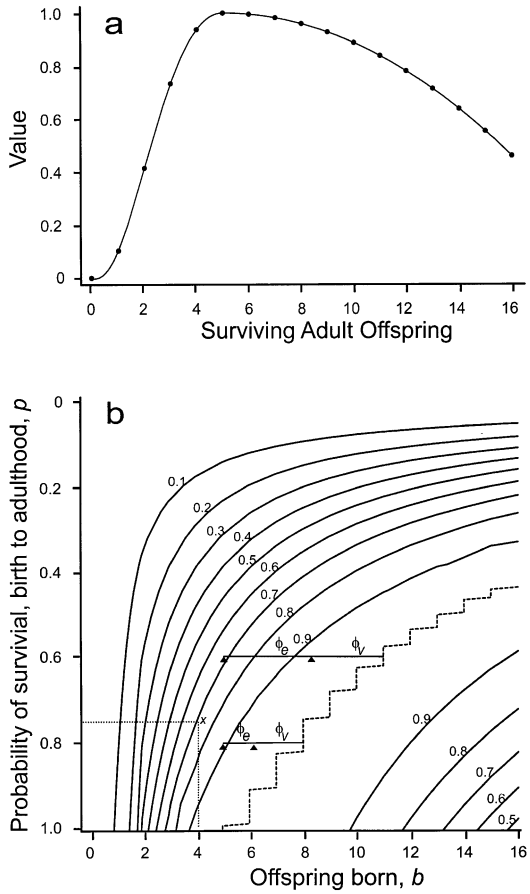

Fig. 2. (a) Proposed right-ibis value function for number of adult offspring of a couple living under the socioeconomic conditions of intensive agricultural production. (b) Iso-value map based on the right-ibis value function shown in (a) and a binomial outcome distribution for survivorship of children (b is the number of live births and p is the probability of their survival to adulthood). Value (fitness, utility) is represented on a scale of 0 to 1. As survival probabilities fall, the optimal, risk-sensitive fertility choice (b*, stair-stepped dashed line) is deflected to the right along the ridge of the contours. This line is stair-stepped because children come in integral units. The best-choice fertility at each value of p can be differentiated into the supplementary births needed to offset the average or expected effect of mortality (ϕ_e) and an additional increment required to offset stochastic variance in mortality (ϕ_v). These relationships are shown for two levels of survivorship (p=0.8 and 0.6). The predicted fertility increment due to stochasticity (ϕ_v) generates positive variance compensation. Strictly speaking, the iso-value map for a noncontinuous function should depict only the integer values, representing whole births (b = 1, 2, 3. . .). For ease of visualization, we have used a graphics smoothing function to connect these points into continuous contours in this and Figs. 4 and 5. The point x corresponds to the calculation in Table 1.

match the peak of this curve at the end of their family cycle. However, as reproductive outcomes become less predictable, the optimum (risk-sensitive) number of births (b*) will shift upward from the deterministic peak. This occurs because the value function imposes significantly higher costs on the chances of ending the family cycle with a smaller-than-

optimum offspring cohort than it imposes on a larger-than-optimum cohort. If couples are optimizing value and are uncertain of completed family size, they will be constrained to somewhat over-produce children.

3.3. The binomial outcome distribution

The long-term outcome distribution for survival is conveniently approximated by a binomial. Each event (birth) is characterized by two alternative states (survival to adulthood, or mortality) with associated odds (p = probability of survival, $1-p$ = that of mortality). The distribution is discrete and it is truncated at 0 and b, where b is the total number of births. The general binomial formula is:

$$f_{\mathrm{b}}(s) = C[b,s]p^{s}(1-p)^{b-s} \tag{2}$$

where $C[b,s] = b!/[s!(b-s)!]$. The term $f_{\mathrm{b}}(s)$ is read as the likelihood of s surviving adult offspring, given b births. The binomial mean (μ) and variance (σ^2) are given by:

$$\mu = bp \tag{3}$$

$$\sigma^2 = bp(1-p) \tag{4}$$

and they are interdependent. For a given b, variance is greatest at $p = 0.5$; this also is the only value of p for which the binomial distribution is symmetrical.

3.4. Results: an iso-value map for stochastic fertility outcomes

Using the right-ibis value function (Fig. 2a) and a binomial distribution of outcomes, we can calculate expected values and generate an iso-value map for the fertility behavior of our generalized peasant agriculturalist (Fig. 2b) under a wide variety of conditions. The equation used is the discrete or noncontinuous equivalent of Eq. (1):

$$E[V(b)] = \Sigma_{\mathrm{s}} V(s) f_{\mathrm{b}}(s) \tag{5}$$

This says that the expected value of b births, $E[V(b)]$, is equal to the product of the value function, $V(s)$, for a particular outcome and the binomial likelihood of that outcome, $f_{\mathrm{b}}(s)$, summed over the range of possible survivorship outcomes, Σ_{s}, 0 to b. This map is the fertility behavior analog of the like representation used for analyzing and comparing risk-sensitive subsistence options (Fig. 1b; see Winterhalder et al., 1999). It differs in that: (a) we have defined the y-axis by probability of survival, p; and (b) unlike the case for the normal distribution, in which an option in the alternative set might be associated with any combination of mean and variance, here the possible b, p combinations are restricted by the co-variation of these factors (Eqs. (3) and (4)). A given set of environmental conditions is reflected in the choice of the value function and p; we then find the b^* corresponding to the highest possible expected value.

Observe that the x-axis of Fig. 2b depicts the situation in which the long-term outcome of a birth is completely predictable. If $p = 1$, the iso-value map is simply a topographical

representation of the value function (2a). As p decreases toward 0.5, unpredictable binomial outcome variance increases and the orientation of the iso-value contours twists to the right. For a given p, one reads right to find the maximum value, located on the stair-stepped (dashed) line, and then down to its associated b or number of births. As predictability (p) diminishes, the optimal risk-sensitive number of births (b*) increases by integer units above that for the deterministic (or $p = 1$) case.

The example in Table 1 helps to explain the form taken by this fertility iso-value map. We set (b) equal to four births and the probability of survival (p) equal to 0.75. If the family could count on the expected average (three surviving offspring), they would achieve a value of 0.74 (see Fig. 2a). But an outcome of three grown children occurs only 42% of the time. There is a 21% possibility that they will end the family cycle with two children; nearly a 5% possibility of only one child. Because of the significant odds and especially the very high cost of the latter two possibilities, the expected value of four births is only 0.70 (as can be confirmed in Fig. 2b, point x). Each point in an iso-value map is calculated in the manner of Table 1.

A risk-sensitive tactic adjusts births so to avoid, in so far as is possible, the sharp lower- or upper-tail costs associated with an asymmetrical value function. The iso-value map allows us to determine the number of births needed to maximize the expected value of the surviving adult sibship. As (p) decreases from 1.0, extra births will result from a mean effect (ϕ_e) *and* a variance effect (ϕ_v). We can isolate the two effects as follows: the optimal family size at $p = 1.0$ is 5. At $p = 0.8$, it is 8, an increase of three births. Only 1.25 of these additional births would be necessary to offset the mean effect of mortality ($5/0.8 = 6.25$). The other 1.75 births are necessary to adjust for the effect of unpredictable variance. A like calculation can be done for any point in this map, illustrating our earlier claim that stochastic variance itself affects which alternative is optimal. We term this shift due to unpredictability (or ϕ_v) the *variance compensation hypothesis* (VCH). For a right-ibis value function, variance compensation commonly is positive; it is an effect over and above average losses, and thus exerts upward pressure on fertility and long-term population growth.

We can make several additional observations concerning this iso-value map of fertility. First, each level of mortality (p) corresponds to a best-choice (b) lying along the stair-step line superimposed on the ridge of the iso-value map. This establishes the best choice birth cohort

Table 1
Calculation of expected value, noncontinuous binomial outcome distribution for four births ($b = 4$), and a likelihood of survival of $p = 0.75$

Outcome (no. of grown children, s)	Binomial distribution (likelihood, $f_4(s)$)[a]	Value [$V(s)$][b]	Weighted value
4	0.316	0.94	0.297
3	0.422	0.74	0.312
2	0.211	0.42	0.089
1	0.047	0.11	0.005
0	0.004	0.00	0.000
Expected value, $\sum_s$:			0.703

[a] See Eq. (2).
[b] From Fig. 2a.

for each environment (each p). Secondly, the line that defines the optimum is not itself an iso-value contour; it decreases in value with distance from the x-axis (this is best seen in Fig. 4b). Stochasticity has a cost, even for the best, risk-sensitive decision about number of births. Third, while the topography of this map is controlled most obviously by the shape of the value function, it also responds subtly to features of the underlying binomial (e.g., variance is greatest at $p = 0.5$; the distribution is skewed for $p \neq 0.5$). However, dominance of the iso-value map by the value function puts a premium on analyzing the features giving value curves a particular shape.

4. Discussion

This fertility iso-value map restates our opening vignette with the analytical specificity of a formal model. If offspring survival is unpredictable to some degree, then to increase their confidence of avoiding very costly shortfalls of children, parents in our hypothesized, right-ibis agricultural households are constrained to somewhat over-produce them. We now examine the implications of this model with respect to several problems in historical demography and evolutionary biology, beginning with demographic transitions. We emphasize here the range of potential applications of the model rather than explicit tests of it because, as we note below, existing demographic data are seldom of a form that would allow for a more empirical appraisal.

4.1. Demographic transitions

The term "demographic transition" refers to the relatively sudden declines in completed family size seen throughout western Europe in the late 18th and early 19th century. Similar although not uniform declines have characterized some regions of the developing world in the 19th and 20th centuries. In general, demographic transitions are associated with increasing wealth, urbanization and industrialization, and with drops in child mortality.

Because of their exceptional importance to issues of population growth, economic development and environmental quality, demographic transitions have drawn sustained attention from anthropology, demography, economics, and sociology (Caldwell, 1982; Kertzer & Fricke, 1997; Livi-Bacci, 1997; Robinson, 1997; Willis, 1987). Recently they have engaged behavioral ecologists, partly because the apparent association of declining fertility with increasing potential to support offspring appears to be a direct challenge to the neo-Darwinian premise that human behavior is designed to promote reproductive success (Boone & Kessler, 1999; Leslie & Winterhalder, 2001; Luttbeg et al., 2000). There are multiple competing hypotheses for the changes recorded in demographic transitions, but it seems a fair appraisal that general models for these processes have not kept pace with growing empirical appreciation that their causes may be diverse and specific to particular locales and situations.

A risk-sensitive approach and the VCH can be used to formulate hypotheses about the role of fertility in demographic transitions. The key is to recognize how environmental, social or

other factors might alter either the outcome distribution or the value function in a direction that would promote lower optimal fertility. There are four general possibilities. Each is novel to the extent that it engages the issue of variance compensation, either alone or in combination with processes like those hypothesized by other demographic theorists. Taking a right-ibis value function as the starting point, a decline in optimal fertility relative to what we have postulated for agricultural production might be the result of:

(1) *Reduced stochastic outcome variance*. Lower mortality, perhaps traced to better diet or health care, would lessen stochastic variance in family size outcomes and thus reduce positive variance compensation. Given circumstances like those depicted in Fig. 2b, the variance compensation effect (ϕ_v) drops from 2.7 to 1.7 extra births as survivorship increases from $p=0.6$ to 0.8. Thus, variance compensation alone might explain why fertility levels dropped during the European demographic transition more than required to offset average increases in survivorship (Luttbeg et al., 2000: 345).

(2) *Elevation of the low-fertility portion of the value function* (Fig. 3; variant a). Any factors that lessen dependence on a threshold (minimum) number of grown offspring would raise the value of low fertility outcomes and reduce positive variance compensation. Such factors might include change in inheritance, provision of more secure or less expensive forms of old age subsistence insurance, reduced need for agricultural labor, or more secure property rights.

(3) *A sharper decline in the high fertility portion of the value function* (Fig. 3; variant b). Socioeconomic changes that increase the relative cost (or decrease the value) of large families, such as expanded workplace opportunities for women, higher educational outlays for children, or an increase in the inheritance required for grown offspring to have a viable start toward their own family's subsistence, might have this effect.

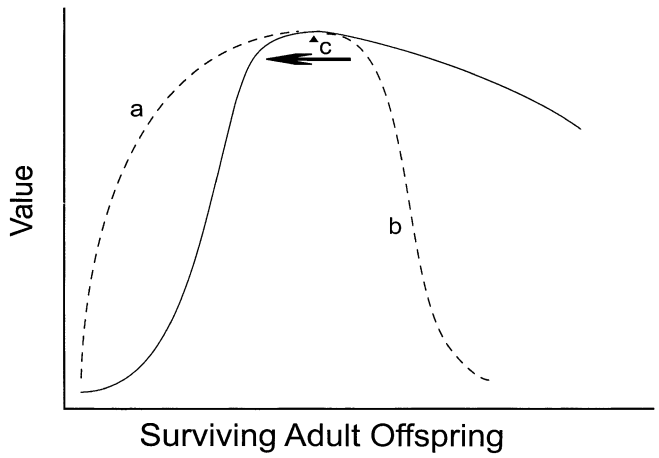

Fig. 3. Pathways to lower fertility via a reduction in positive variance compensation. Changes in socioeconomic, environmental, or other conditions might reduce the fertility-elevating effects of positive variance compensation by a reduction in stochastic variance in mortality, or by changes in the value function. The latter include: (dashed line "a") elevation of the low-fertility portion of the value function; (dashed line "b") a sharper decline in the high-fertility portion of the value function; and/or (arrow "c") a left shift in the maximum of the value function.

(4) *A left shift in the peak of the value curve* (Fig. 3; variant c). A leftward shift in the right-ibis curve will mimic process (2), as it eliminates the sharp cost of low fertility outcomes (except, of course for $n = 0$). In this case, however, the fertility drop due to reduced variance compensation will be augmented by the mean shift in the peak of the value function.

To summarize, under conditions of positive variance compensation, reduced fertility would be predicted from any socioeconomic or environmental factors that: (i) lessen the unpredictable variance associated with long-term reproductive outcomes; (ii) lessen the detriments associated with unusually low fertility; (iii) increase the detriments associated with unusually high fertility, or (iv) move leftward the peak of the value function. This means that virtually all of the existing socioeconomic hypotheses about fertility transitions may have a risk-sensitive aspect to them. This approach is consistent with empirical experience showing that demographic transitions may have diverse sources of local causation. We do not know whether or to what degree the model can be verified using this same evidence.

4.2. Population and intensification

The shape of the right-ibis value function rests in part on the relatively low cost of erring toward a larger-than-optimal family size. We proposed that this is a consequence of the elasticity of agriculture to family labor intensification. This is an intra-familial process that can be designated "micro-intensification." It may be possible to link micro-intensification and variance compensation to the developmental process known in the literature as *agricultural intensification* (Boserup, 1965; Brookfield, 1972, 1984). To keep our terminology consistent, we call the latter "macro-intensification."

Macro-intensification refers to the long-term process by which allows are shortened and inputs of labor, capital, and skill are increased relative to a constant area of land. Intensification obtains a greater yield from a given field area by substituting the efficacy of these inputs for the productivity of nature at lower levels of management. It economizes the use of land (Brookfield, 1972: 32). In the classic formulation of Boserup (1965), intensification is driven by population pressure and it is generally responsible for the elaboration of extensive agriculture into its diverse and intensive contemporary forms. As human density increases, declining *per capita* agricultural returns lead to (a) shifts from extensive to intensive cultivation, (b) shortening of fallow, (c) the innovation and application of more elaborate and effective technology, (d) multicropping, and (e) other intensive techniques. In some treatments, population pressure is augmented or perhaps supplanted by socioecological factors such as resource requirements for trade or ritual activities (the "pressure of needs"). Similarly, population pressure may be affected by ecological constraints (Brookfield, 1972, p. 44). In another scenario, socioeconomic demands for a surplus, perhaps imposed by a dominant and exploitative class, drive the process (Brookfield, 1984).

The Boserup model has spawned an enormous literature, not only in demography (Livi-Bacci, 1997) and development studies (Boserup, 1981), but in geography (Brookfield, 1972, 1984) and anthropology as well (recent summaries in Netting, 1993; Stone, 1996; Stone & Downum, 1999; Wood, 1998). Archaeologists and prehistorians have debated the model

widely because of its possible relevance to explaining the origins of agriculture (Price & Gebauer, 1995) and of state-level political organization (Hassan, 1981).

In Boserup's approach, population is an exogenous and unexplained variable. Population growth is taken as an ever-present tendency which, when it does occur, will have the patterned developmental consequences identified. Brookfield (1972, p. 35) echoes this treatment—"Now allow population to increase at a steady rate." It would of course be theoretically desirable to bring population itself within the model and to give specific reasons for its exerting pressures on certain forms of agricultural production.

To achieve that, we propose that positive variance compensation and thus risk-sensitive tendencies toward population growth are likely to occur in the same conditions that Boserup identified as guiding the resulting population pressure into agricultural intensification. For instance, assume that the inheritance and old-age subsistence hazards of too few grown children, coupled with the elasticity of family farming in the face of extra offspring (its capacity for micro-intensification) generates a right-ibis value function. Positive variance compensation constrains families to somewhat over-produce children, and the resulting population pressures generate macro-intensification in the manner envisioned by Boserup. There could be positive feedback in this relationship. Suppose that an initial increase in human population density occasioned by higher agricultural yields created conditions that promoted infectious disease (Cohen, 1989), thereby elevating randomly acting, pre-adult mortality. This would increase unpredictable outcome variance and selection pressures for risk-sensitive fertility adjustments. Enhanced positive variance compensation then would become a consequence of macro-intensification even as it was fueling it.

Although speculative, this proposal has the merit that (i) population, and specifically fertility, is brought within the same system of explanatory variables that characterize the process of macro-intensification, and (ii) the combined model can show how certain configurations of those variables create tendencies that simultaneously stimulate population growth and long-term technological changes in production and land use. High fertility and agricultural intensification both may be the result of adaptive reproductive choices responding to the constraints and uncertainties of intensifying agricultural production.

4.3. Comparative fertility analysis using the VCH

At least some socioeconomic circumstances affecting peasant agriculture may give rise to a right-ibis value function. We now extend this argument by considering the complementary, left-ibis function depicted in Fig. 4a. From the origin, it is concave downward, rising slowly to a peak from which it declines rapidly into a short convex segment. Its asymmetry around the intermediate peak (set arbitrarily at $n = 5$) is its most salient feature. This function will occur in situations in which (a) the value curve decelerates as births are added to a low fertility cohort, and (b) there is an abrupt upper cap on the capacity of supra-peak numbers of offspring to succeed, perhaps because their parents' or their own resources are sharply limited. Examples might include parents facing steep higher education costs, or peasant agriculturalists who have exhausted possibilities for household micro-intensification and who have few alternatives for placing excess children in productive situations. In this circum-

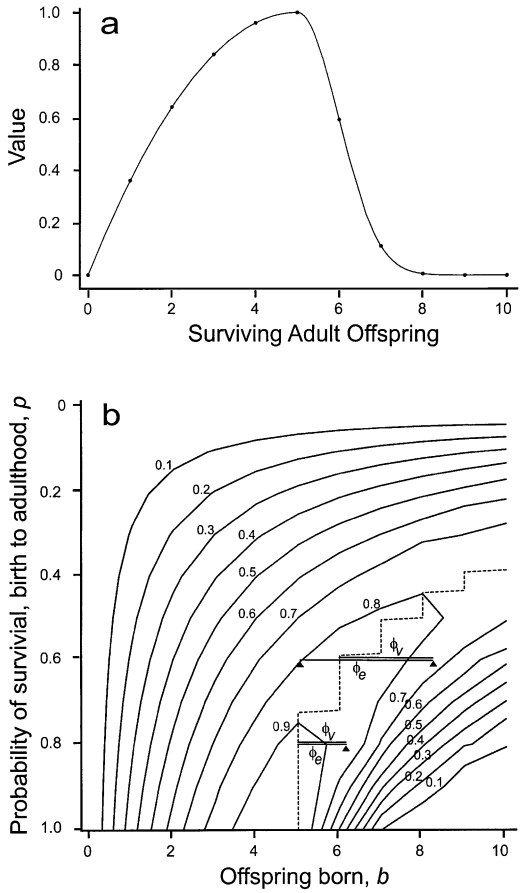

Fig. 4. (a) A left-ibis value function, and (b) the corresponding iso-value map, assuming a binomial outcome distribution for survivorship of children. Value (fitness, utility) is represented on a scale of 0 to 1. The optimal fertility (stair-stepped, dashed line) is deflected to the right as survival drops. Optimal fertility can be differentiated into the supplementary births needed to offset the average effect of mortality (ϕ_e) and an increment required to offset stochastic variance (ϕ_v). These relationships are shown for two levels of survivorship ($p = 0.8$ and 0.6). Here, the stochastic increment (ϕ_v) is negative; it decreases fertility. The optimal, risk-sensitive number of births for a left-ibis function is *less* than would be required to offset the mean or expected effects of mortality, creating a situation of negative variance compensation.

stance, a couple, seeking to avoid the costly happenstance of too many surviving offspring, will have *fewer* births than needed to offset expected average mortality. Their best option entails negative variance compensation (Fig. 4b).

Hunter–gatherers, for instance, may offer an instance of negative variance compensation. Typically, aging foragers are not so dependent as are agriculturalists on grown children for direct subsistence or continued access to means of production, as nonlineal avenues for social welfare are well-developed in these societies. In cases of high mobility, they also may face tight constraints on short birth intervals, thus on the production of large numbers of offspring

(Blurton Jones, 1987, 1994; Blurton Jones & Sibly, 1978). The combination of such factors may produce a left-ibis value function, and dampen reproduction among natural-fertility foragers relative to agriculturalists (Bentley, Goldberg, & Jasienska, 1993; Bentley, Jasienska, & Goldberg, 1993; Sellen & Mace, 1997).

Although the form and degree of variance compensation may be associated quite generally with mode of production (e.g., foraging, horticulture, pastoralism, agriculture or industrial capitalism), we believe the more promising comparative possibilities lie at more specific levels of analysis. Borgerhoff Mulder (2001) shows that Kipsigis farmers suffer from over-producing children. Their small farmsteads can not be subdivided, and as a consequence extra children produce few grandchildren. By contrast, the extra children of Datoga pastoralists do much better, the result of greater "elasticity" of herding in response to labor. These situations would produce quite divergent value functions.

4.4. Clutch size and variance compensation

In a series of classic papers, David Lack (1947, 1948a, 1948b, 1954) developed the proposition that clutch size in birds is set by natural selection so that it corresponds to the maximum number of offspring that can be raised to maturity. Lack's model entails a trade-off: the greater the number of eggs produced, the fewer the resources that parents can provide to any one of them and the lower the likelihood that an egg will successfully reach the fledgling or adult/reproductive stage. In support of his idea, Lack cited observations like this one on the common swift (*Apus apus*), suggesting an intermediate optimum clutch size:

> Nearly all the losses were due to starvation, broods of 3 suffering more than broods of 2 because the food was at first shared among three mouths instead of two. As a result, broods of 2 gave rise on the average to 1.6, and broods of 3 to 1.4, survivors per brood. . . (Lack, 1954, p. 144).

The clutch- (or litter-) size model has been extended to non-avian taxa and has stimulated a large theoretical and empirical literature on the evolution of fertility (review in Godfray, Partridge, & Harvey, 1991). Generalized graphical representations of the model (e.g., Pianka, 2000, p. 162) typically depict total parental fitness as a concave downward, parabolic function of the number of offspring born. Thus represented, the Lack model is a reproductive value function, and our VCH is a risk-sensitive application of it. If offspring survival is stochastic and we make the assumption that the total fertility curve generally is asymmetric in the manner hinted by the swift evidence (above), then clutch-size variance compensation will be positive in most cases (Fig. 5; see Winterhalder, Leslie, & Weiss, 2001). In addition to its empirical implications — parents generally will hedge by producing more offspring than corresponds to the Lack optimum number — this is theoretically important to neo-Darwinism itself. If positive variance compensation in fertility is common, it joins the several other factors identified generally as causing overproduction of offspring (Mock & Forbes, 1995) and thus as a driving force in evolution by natural selection: "Hence, as more individuals are produced than can possibly survive, there must in every case be a struggle for existence. . ." (Darwin 1872, p. 53).

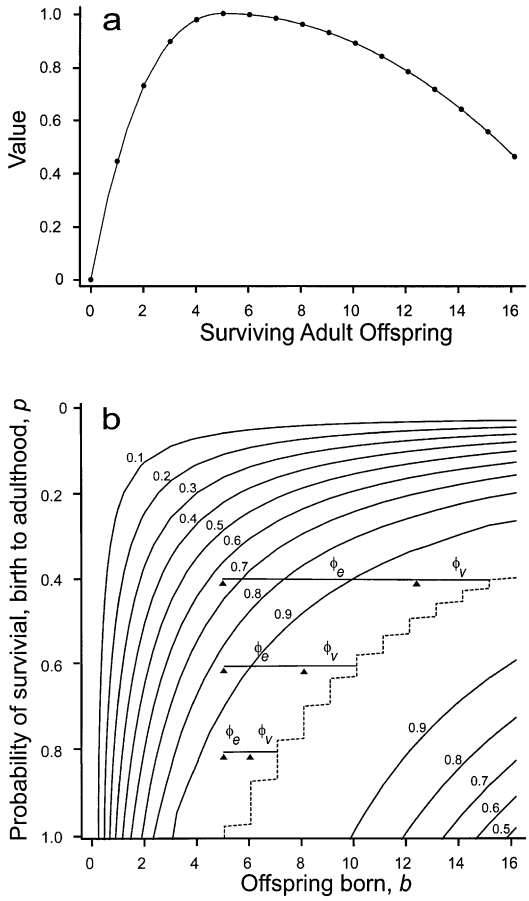

Fig. 5. Clutch size and variance compensation. (a) Total fitness as a function of clutch- or litter-size and (b) a corresponding iso-value map. This value function assumes that a sub-peak fertility exacts a higher total fitness cost than supra-peak fertility. If value (fitness) is asymmetric in the manner shown, then risk-sensitive fertility adjustments will entail positive variance compensation. Optimal fertility can be differentiated into the supplementary births needed to offset the average effect of mortality (ϕ_e) and an increment required to offset stochastic variance (ϕ_v). These relationships are shown for three levels of survivorship ($p = 0.8$, 0.6, and 0.4). The fitness-maximizing tactic requires that parents produce a greater number of births than would be ideal in nonstochastic circumstances.

4.5. Caveats, complications, and entailments

4.5.1. The evolutionary approach

Behavioral ecology shares with microeconomics the methodological assumption that behavior tends to optimize the match of means to ends in constrained circumstances (Smith & Winterhalder, 1992; Winterhalder & Smith, 1992). However, because of their appeal to evolutionary processes, behavioral ecologists need not presume that such behavior is always or exclusively the result of a rational individual calculation of costs and benefits (see Siegers,

1990). Instead, it may be motivated by custom, rules of thumb or other sociocultural conventions to which individuals subscribe and on which they act. We assume—not always correctly—that the rationality of the action has been coded into these conventions by evolutionary processes selecting on cultural inheritance (Boyd & Richerson, 1985; Durham, 1990, 1992), perhaps guided by underlying, genetically based predispositions that have evolved by natural selection (Smith, 2000). Thus, in using an evolutionary approach we need not presume that each individual apes the analytical tools and accumulated insights of academicians, with their value functions, probability distributions and advanced graphics software. We also deflect a glib if all too frequent critique, which claims that since individuals either are incapable of such calculations or do not routinely experience making them, the economic approach is nugatory. Perhaps more importantly, we have immediate theoretical reasons to be drawn into study of the diverse and localized, sociocultural determinants of behavior and their history.

4.5.2. The two-stage assumption versus continuous adjustment

In order to facilitate constructing a model we made several unrealistic assumptions about fertility behavior. Prominent among them, we reduced the life history of a couple to a two-stage phenomenon. Births are set at the beginning of the family cycle and the outcome is experienced a generation later. In reality, fertility behavior in humans allows for some degree of continuous adjustment, conscious or unconscious. Through "stopping behavior" and "reproductive compensation" young parents can adjust for some of the chance events affecting long-term fertility outcomes (Voland, 1995). For instance, should all stochastic deaths occur before age 5, then a couple with a target number of children who have survived past that age has effectively eliminated unpredictability. However, the possibility of such adjustment is incomplete and it diminishes over time, especially if significant unpredictable mortality falls on older children. The passing of opportunities and aging make some decisions irreversible and foreclose on others.

Overall, if the reproductive pattern allows a dynamic process of fertility adjustments, as for humans, this should reduce the risk associated with long-term fertility outcomes. If this is the case, our simple, two-step model may overestimate the potential importance of variance compensation. While the greater realism of a dynamic reproductive decision process will not change the value function itself, it may modify the iso-value map by modifying the distribution of outcome probabilities. It is more likely to reduce the quantitative magnitude of variance compensation than to alter its qualitative features. Dynamic programming (Luttbeg et al., 2000) may be a useful analytical technique here. For instance, Mace (1996 1998; Mace & Sear, 1997) uses this technique to model the effects of changing levels of mortality on reproductive decision-making about replacement behavior.

If we restrict ourselves to a currency of utility, fostering and adoption of children (e.g., Sieff, 1997, p. 523) may serve as a means of avoiding the consequences of the over- or underproduction of offspring. In fact, these behaviors may signal situations in which long-term fertility outcomes are risk-sensitive. By contrast, if the currency is Darwinian fitness, the efficacy of adoption and fostering will be reduced as a function of the coefficient of relationship between parent and adopted or fostered child.

4.5.3. Mortality by other means

We likewise simplified by assuming that a live–die (1, 0) mortality exhausts the stochastic factors relevant to family building. In fact, a child might live but abandon the family through emigration; he or she might remain home but default on providing expected welfare services. The ideal completed family might entail a particular sex ratio (Leslie & Winterhalder, 2001), thus, compounding the unpredictability of survival and filiality with that of sex ratio. If factors such as these are cogent, then our simple, mortality-based model will significantly underestimate the potential significance of variance compensation.

In this more realistic sense of family goals, (i) outcomes can be matters of degree (the child that provides only partial support for aging parents); (ii) outcomes are afflicted by more sources of uncertainty than those associated with mortality as such; and (iii) we are forced to confront our earlier gloss on the currencies of utility and reproductive fitness. A child that emigrates or otherwise defaults on providing welfare services to parents reduces its utility to them but possibly not its fitness. Here, as in the case of fostering and adoption, economic and evolutionary currencies have the very useful analytic potential to make diverging predictions.

4.5.4. Circumstances, children, and parents are diverse, within and among societies

In developing the VCH we set aside the possibility that subgroups in a population experience significantly different environments. Likewise, we ignored divergences between males and females (Borgerhoff Mulder, 2001), and dissimilarities among children (Borgerhoff Mulder, 1998). The formal expression of these assumptions of homogeneity is the use of a single population-wide value function and outcome distribution in making a prediction. We can easily introduce greater realism by comparing model predictions while varying such features. For instance, class differences among the families in a society may give rise to quite different value functions or outcome distributions for children (varying p), leading us to predict intra-societal divergence in fertility behavior or differences in the timing of fertility behavior changes. Male and female adults may weigh differently the factors affecting value functions. Male and female children may have differing potentials for realizing utility or reproductive success. The variety and importance of such factors is evident in Voland's (1995) (also Smith & Smith, 1994; Kaplan, 1996) historical demography research (18th and 19th century) on the Krummhörn region of Germany. Making iterated predictions while changing such features will demonstrate the flexibility and comparative potential of the model (cf. value functions in Figs. 2, 4, and 5).

4.6. Data: fertility behavior and measuring variance

Our case for the VCH has been constructed on the basis of theoretical plausibility and broad analytical promise. However, we have found that the existing literature offers little information suitable for testing the model. Several kinds of empirical evidence will be needed. The direction and magnitude of variance compensation are functions of the shape of the value function, and the degree and form of the unpredictability affecting survivorship. Consequently, to test the model we would need to know: (1) The value functions for population subgroups with differing socioenvironmental contexts; (2) The survivorship

distributions for these groups; and (3) If there is evidence that reproductive behavior reflects the sorts of adjustments predicted by the VCH. This will require that we match population level study with that focused on households and individuals (Caldwell, 1982; Low, 1993; Voland, 1995, 2000). Such data will have to be sufficiently detailed to adjust for methodological complications such as phenotypic correlation (Hill & Hurtado, 1996; Winterhalder & Smith, 2000). Long-term or especially detailed ethnographic study (Borgerhoff Mulder, 1995; Little & Leslie, 1999) and historical demography using such sources as parish and tax records (Low, 1993; Voland, 1995, 2000) may offer our best opportunity for this work.

5. Conclusions

How many children should a couple bear at the beginning of the family or household cycle in order to be assured, to the greatest degree possible, the optimal number of able-bodied adult offspring at its end? If there is unpredictable variability in the outcome, and if the value function for completed family size is nonlinear, then variance compensation may be a significant element of the answer to this question. We conclude with brief comments at three levels:

First and most generally, the VCH model can serve as an heuristic framework for deriving fertility behavior predictions from a wide variety of socioeconomic and environmental variables. The effective determinants of demographic behavior may vary according to case and historical setting, yet be instances of a common process amenable to analysis within a general approach. Demographic transitions may be an instance of the same kind of factors as drive agricultural intensification. The goal is to combine the analytical clarity and specificity of a simple, economic model with an evolutionary framework designed to admit a broad range of biosocial variables.

Second, we have given tentative reasons for thinking that right-ibis and left-ibis value functions of varying degrees may be associated with population-specific diversity within modes of production. Variance compensation may help to explain reproductive differences among natural fertility populations. It also may be an important component in the explanation of fertility transitions, agricultural (macro-) intensification, and clutch size.

Finally, we hope our discussion of risk-sensitivity will provoke demographers and other behavioral scientists to pay greater attention to questions of variability and dispersion. Some demographic puzzles may arise from too exclusive a focus on central tendencies at the expense of analytically relevant stochasticity and variance. Too often we have treated unpredictable variance as if it is noise rather than an important feature of the behavioral setting and a causal element in the evolution of adaptive responses.

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