



Evolved attitudes to risk and the demand for equity

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The equity premium puzzle refers to the observation that people invest far less in the stock market than is implied by measures of their risk aversion in other contexts. Here, we argue that light on this puzzle can be shed by the hypothesis that human risk attitudes were at least partly shaped by our evolutionary history. In particular, a simple evolutionary model shows that natural selection will, over the long haul, favor a greater aversion to aggregate than to idiosyncratic risk. We apply this model—via both a static model of portfolio choice and a dynamic model that allows for intertemporal tradeoffs—to show that an aversion to aggregate risk that is derived from biology may help explain the equity premium puzzle. The type of investor favored in our model would indeed invest less in equities than other common observations of risk-taking behavior from outside the stock market would imply, while engaging in reasonable tradeoffs over time.

attitudes toward risk | aggregate risk | idiosyncratic risk | equity premium puzzle | risk-free rate puzzle

This paper lies in lightly explored territory between biology and economics, in which the utility functions used in economics are informed by results on biological evolution. This approach contrasts with the conventional axiomatic approach in economics. Consider, for example, the human fondness for sweet or fatty foods. These preferences presumably arose among our distant ancestors and plausibly reflect the nutritional and fitness value of such foods in an often difficult and unpredictable environment. These preferences are not, however, always appropriate in present postagricultural and wealthy societies. But the existence of such preferences is plausible evidence that our biological histories shape some of our preferences and aversions. (This argument is drawn from ref. 1.)

The aspects of preferences that are the most promising candidates for biological explanation are aspects that are basic and so would have been important for humans throughout our history (2). One of these aspects concerns time preference (see ref. 3, for example). Another aspect concerns attitudes to risk, which is the focus here.

The Evolutionary Context. We hypothesize that attitudes to risk are at least partly hardwired and so persist even if there is no longer a strong link, or any link at all, between material success and fitness. (See ref. 4 for evidence that risk attitudes are also shaped by culture.) What attitudes toward risk might then be favored by natural selection? A specific and striking evolutionary prediction is that individuals ought to be more averse to aggregate risk—where a single public coin generates the same outcome for everyone—than they are to comparable idiosyncratic risk—where multiple independent coins generate the outcomes (1). We will argue that this provides a novel resolution of the “equity premium puzzle”—the “excessive” aversion investors typically display to stock market risk.

We follow the basic approach of Robson (1), which involves perhaps the simplest possible biological model. Risk-taking behavior in a random environment is controlled by alternative genes (alleles) at a single “locus.” These alleles induce differ-

ent risk behaviors and so compete to fill this locus. The model is haploid and asexual and features discrete generations with no carrying capacity or density dependence. (A species is haploid if it carries a single copy of each gene, and it is asexual if there is no mixing of genetic material inherited from two parents when producing gametes.) A branching process model that allows extinction shows, among other things, that the type that maximizes the expected logarithm of offspring number over the environments encountered ultimately dominates the population.

Several of Robson’s results reflect findings from the economic literature—for example, on portfolios that maximize wealth in the distant future (5). His results also echo those from the biological literature on the population genetics of evolution in random environments—in particular, the classical “geometric mean principle.”* In a two-allele haploid model where fitness (probability of survival) fluctuates randomly through time—reflecting random environments encountered over discrete generations—the allele with the higher geometric mean fitness will tend to ultimately displace the other allele (7–9). (Apparent “balancing” selection arising from temporal variation in fitness cannot, therefore, maintain both alleles in a haploid population; i.e., see ref. 9.)

Although the allele with the higher geometric mean fitness tends to dominate the population over the long haul, its expected frequency does not always increase; rather, this depends on current allele frequencies. See ref. 10 for this and other concerns about the universality of the geometric mean principle.

In the end, the extent to which evolution has endowed us with particular attitudes to risk is an empirical question. Here, we

Significance

An important puzzle in economics concerns the equity premium. Why does anyone hold bonds given the option of holding stocks? Stocks are riskier, but they do much better on average in the long run than bonds, thus generating the equity premium puzzle. Standard economic models of preferences have difficulty accounting for this anomaly on the basis of a level of risk aversion that is consistent with risk-taking behavior elsewhere. We show that considering the biological basis of preferences is fruitful here. Biological evolution predicts that individuals should be more averse to aggregate—shared—risks than they are to risks that are idiosyncratic—personal. Since the stock market involves aggregate risk, this helps to resolve the puzzle.

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*The geometric mean of a random variable is the exponential of the expected logarithm of the variable. The literature on bet-hedging builds on such results (see ref. 6, for example).

merely ask if the simple evolutionary scenario described above sheds light on the equity premium puzzle.[†]

Evolved Attitudes to Aggregate and Idiosyncratic Risk. The differential impact of aggregate and idiosyncratic economic gambles on biological success is considered in ref. 1.[‡] These results can best be illustrated by examples. Consider two types of individuals within an asexual species in a discrete-time setting.

In each period, Type 1 has either 1 or 2 offspring, each with probability 1/2, and this risk is “idiosyncratic,” that is, independent across all individuals and periods. Assume that there is no density dependence, that the population has size 1 at $t = 0$, but the population is “large,” so that the per period growth factor is always exactly 3/2. It follows that the number of Type 1 individuals at t is then $x(t) = (3/2)^t$. As a purely formal matter, although this is a discrete-time setting, it is convenient to use the equivalent continuous time growth rate $\frac{\ln x(t)}{t} = \ln(3/2)$.

On the other hand, although Type 2 individuals again have either 1 or 2 offspring, each with probability 1/2, the risk is now “aggregate,” in that all individuals in each period either have 1 offspring or all of them have 2.

Suppose that the initial population of Type 2 at $t = 0$ is also 1. Even if this population is also “large,” the number of Type 2s at period t is necessarily random, given by $\tilde{y}(t) = 2^{\tilde{n}(t)}$, where $\tilde{n}(t)$ is the random number of heads in t flips of a fair coin. It follows from the strong law of large numbers that a limiting continuous growth rate exists since $\frac{\ln \tilde{y}(t)}{t} = \frac{\tilde{n}(t)}{t} \ln 2 \rightarrow \ln \sqrt{2} < \ln(3/2)$, with probability 1, as $t \rightarrow \infty$.

The evolutionary dominance of Type 1 over Type 2 then follows from the relationship between the limiting growth rates. We have $\frac{\ln x(t)/\tilde{y}(t)}{t} = \frac{\ln x(t)}{t} - \frac{\ln \tilde{y}(t)}{t} \rightarrow \ln(3/2) - \ln(\sqrt{2}) > 0$, with probability 1, so that $\frac{x(t)}{\tilde{y}(t)} \rightarrow \infty$, with probability 1, as $t \rightarrow \infty$. Hence, Type 1 is the unambiguous evolutionary winner in the long run.

Although this race is simple in that it lacks interactions between the types, it shows how certain preferences may be favored by evolution. Given the choice, individuals should strictly prefer idiosyncratic risk over aggregate risk with the same distribution. (These findings are related to those from population genetics on “genotypic homeostasis” in a fluctuating environment; i.e., see ref. 10.)

It is worth noting that, although Type 2 is unambiguously beaten in terms of a compelling criterion, it does not always simply lag behind Type 1. Indeed, the mean of Type 2 keeps pace with Type 1. That is, since $E\tilde{y}(t) = (3/2)^t$, for all t , it follows that $\frac{\ln E\tilde{y}(t)}{t} = \ln(3/2)$ for all t .[§] Hence, for finite t , there are many outcomes where $\tilde{y}(t) > x(t)$. There must then be sequences with substantially more 2s than 1s, in order to maintain the growth rate of the mean of the Type 2 population at $\ln(3/2)$. In the limit, however, the probability of all sequences that do not have a precisely equal number of 1s and 2s tends to 0, and the limiting growth rate of the Type 2 population is only $\ln \sqrt{2}$. (Similar

results in a biological context are in ref. 12; they are applied in economics in ref. 13.)

Perhaps the simplest way of converting this biological argument to an economic example is to suppose that expected offspring are produced as $\Psi(c)$, where $c \geq 0$ is consumption and the nondecreasing Ψ is a biological production function. Suppose that $\Psi(c_1) = 1$ and $\Psi(c_2) = 2$. The present example then implies that individuals who experience an idiosyncratic gamble over consumption levels c_1 and c_2 will outperform those who experience an aggregate gamble over c_1 and c_2 , where, in both cases, c_1 and c_2 have equal probability.

More explicitly, suppose these consumption outcomes c_1 and c_2 for Type 2 are generated by aggregate states A and B , respectively, where these occur independently across periods. The Type 1 population, however, is unaffected by the state, so that c_1 and c_2 occur independently across individuals with equal probability in either state. If the individual can choose between the idiosyncratic gamble over consumption and the aggregate gamble, she should strictly prefer the former, despite the two gambles being identical from a purely individualistic point of view.

This example can be sharpened, so that Type 2 has one offspring with probability p and two offspring with probability $1 - p$. That is, there exists $p < 1/2$ such that Type 1 still outdoes Type 2. From a strictly individualistic point of view, this contradicts first-order stochastic dominance or probabilistic sophistication, more generally. The most successful type is not individualistic but takes the outcomes of others into account. (See refs. 1 and 3 for further discussion of the issues this raises.)

This example can also be dramatized in a way that is relevant to the present application. Although zero offspring is bad from an idiosyncratic point of view, it is catastrophic from an aggregate point of view. Suppose, that is, that Type 1 has either zero offspring, with probability $p \in (0, 1/2)$, or two offspring, with probability $1 - p$. The expected number of offspring is then $2(1 - p) > 1$ and the limiting continuous time growth rate is $\ln(2(1 - p)) > 0$.[¶] Type 2 also has zero offspring, with probability $p \in (0, 1/2)$, or two offspring, with probability $1 - p$, but these outcomes are aggregate. The limiting growth rate for Type 2 is then $p \ln 0 + (1 - p) \ln 2 = -\infty$. This reflects the inevitable extinction of Type 2, which happens in the first period that all individuals generate zero offspring. (The evolutionary dominance of Type 1 over Type 2 holds if Type 2 has any probability $q > 0$ of zero offspring.)

The most general case treated in ref. 1 is as follows. Suppose that there are random aggregate states denoted by s . These states are drawn independently from a given distribution in each of an infinite number of periods. In each such state s , consumption outcomes are random and independent across individuals conditional on the state s . Suppose that $\Psi(x)$ is the expected offspring produced by any x . Expected offspring in state s is then $E(\Psi(x)|s)$. The limiting growth rate of the population is then the expectation over the states of the logarithm of the expected offspring conditional on the state:

$$\ln E(\Psi(x)|s) < \ln EE(\Psi(x)|s) = \ln E(\Psi(x)). \quad [1]$$

The inequality reflects that the individual prefers aggregate risk to be converted to comparable idiosyncratic risk. The biological reason for this preference is that idiosyncratic risk can be diversified within the population, but aggregate risk cannot. When this distinction is embedded in preferences, the mere possibility of such biological diversification generates less risk aversion for idiosyncratic risks than for aggregate risks for the individual.

[¶]In the more general branching process model ref. 1, with a finite initial population, $2(1 - p) > 1$ ensures that the population can grow to infinity.

[†]Another instance of aggregate risk concerns disease outbreaks. For example, at least with the benefit of hindsight, the resources devoted to the novel “mad cow disease” per likely casualty now seem disproportionate to those devoted to more familiar heart disease. Although there are undoubtedly other relevant factors, this could be partly due to the more pronounced element of unknown shared risk for the former disease—concerning its mechanism of transmission, for example.

[‡]It is argued in ref. 11 that risk aversion in general might have arisen from the greater aversion to aggregate risk than to idiosyncratic risk that is discussed here. This involves an apparent evolutionary “mismatch” in that current idiosyncratic risk is treated in the way that aggregate risk should once have been treated. The current paper supposes, on the other hand, that individuals continue to discern the distinction.

[§]It indeed follows that $\frac{E\tilde{y}(t)}{\tilde{y}(t)} \rightarrow \infty$, with probability 1, as $t \rightarrow \infty$. That is, intriguingly, the mean of the random variable $\tilde{y}(t)$ grows faster than does $\tilde{y}(t)$ itself (1, 2).

Although this distinction arises in a dynamic setting—reflecting how aggregate outcomes compound over time—the appropriate criterion has a formally static representation. This particular representation arises because the age structure of the population is degenerate with only one adult age. (We sketch an extension below in *A Simple Dynamic Model* to a population with two adult ages, where the criterion is explicitly dynamic.)

However, ref. 14 shows that the distinction between aggregate and idiosyncratic risk disappears in a continuous time model, where consumption and offspring are treated as “rates.” They assume that there is no variation with age in mortality or fertility.

In continuous time with a general age structure, ref. 15 shows that the distinction between aggregate and idiosyncratic risk remains as long as mortality or fertility vary with age, although the simplicity of the criterion from ref. 1 is generally lost. Indeed, it is possible that an individual even prefers aggregate risk to strictly comparable idiosyncratic risk. One simple case where there remains greater aversion to aggregate risk than to idiosyncratic risk is where there is a lag to first reproduction, or menarche. This lag plays the role of the period in discrete time.

The model outlined above generates a distinction between idiosyncratic and aggregate risk that is captured by a logarithmic transformation of Ψ for the latter case. This is a specific tilt in favor of idiosyncratic risk. What is crucial is not the precise shape of the logarithmic function but that it reflect the disastrous aggregate consequences of offspring levels near zero. This qualitative property will hold for many other functions.

Convex–Concave Ψ in Biology and Economics. The second key element of the model here is the assumption that the biological production function Ψ is at first convex and then concave. It is important then to defend the empirical plausibility of an initial convex range, in particular. We do this with evidence first from biology and then from economics.

A convex–concave production function is not canonical in biology, but it has been invoked in several scenarios. Perhaps the best known of these is a behavioral ecological scenario. This concerns an organism that confronts an environment that either meets its energetic (nutritional) needs for survival on average or an environment that does not.

In the latter case, the optimal foraging strategy is risk-loving: if one does not expect, for example, to survive the day on the nutrients typically available, then risky foraging behaviors are favored as one may get lucky, obtaining a large enough payoff in food to survive. Reductions in food are essentially inconsequential as one did not expect to survive anyway. Alternatively, if one does expect to survive the day, then risk-averse foraging behaviors are favored, as now the downside with a potential failure to survive is highly consequential.

Mathematically, these intuitions are captured in the behavioral ecology literature via a convex–concave production function (16–18). A large empirical literature provides some support for this model (reviewed in refs. 16 and 19). However, complications have been noted, and alternative hypotheses have been proposed. (See ref. 20 for a critical review of this and related literature.)

An evolutionary account of attitudes to risk in economics is provided in ref. 21. In particular, this hypothesizes that risk-taking at low levels of wealth would be evolutionarily advantageous if such levels already preclude obtaining a mate, so that a loss would be inconsequential, whereas sufficiently large gains would enable a mate to be obtained.

In economics, there is also evidence of human economic risk-preferring behavior among poorer individuals (22). Demand for state lotteries, which are actuarially unfair, is highest among those with the lowest incomes. As incomes rise, individuals shift to stocks. This is not evidence of risk-loving, of course, since the stock market is actuarially advantageous.

Finally, a convex–concave payoff function is a salient feature of prospect theory, where a reference point marks the transition from the convex range to the concave. This theory is advocated in ref. 23 and buttressed with rich empirical evidence. The endogeneity of the reference point is a key part of prospect theory. It may ultimately be useful to make the transition here endogenous also but this is left for future work.

Equity Premium Puzzle. Since we argue that the distinction between idiosyncratic and aggregate risk can help resolve the equity premium puzzle, we now describe this puzzle and previous attempts to resolve it.

There is a profound difficulty in reconciling long-run data on the stock and bond markets with economic theory, as vividly established in ref. 24. That is, in a basic additive model of preferences for consumption over time and risk, it is very difficult to explain why people hold any bonds at all given the vastly superior average return on stocks (Fig. 1).[#]

Although stocks are clearly riskier than bonds, an implausible degree of risk aversion is needed to achieve a reconciliation. The implausibility arises because other evidence on attitudes to risk implies more moderate estimates of risk aversion. Some evidence on more moderate risk aversion derives from property or liability insurance. For example, ref. 26, using US data on property and liability insurance, estimates that the coefficient of relative risk aversion is between 1.2 and 1.8. We argue that it is important to observe that the property or liability insurance considered in ref. 26 largely concerns idiosyncratic risk for a single property or business. Only a small fraction of the total premiums paid for property insurance, for example, covers earthquakes, hurricanes, or multiple properties.

The standard additive model of preferences tightly links attitudes to risk and intertemporal tradeoffs, which makes it more difficult to evaluate the source of the problem posed by the equity premium puzzle. That is, imposing a high degree of risk aversion may also distort intertemporal choice.

A pioneering approach is taken in ref. 27, which constructs a recursive nonadditive model of preferences over consumption streams that allows risk aversion and intertemporal inequality aversion to be independently chosen. However, the best estimates in ref. 28 are that the elasticity of intertemporal substitution is less than 1 and the coefficient of relative risk aversion is close to 1. They do not then claim to resolve the equity premium puzzle.

Another approach to untying risk aversion and intertemporal choice is taken in ref. 29. The author makes the illuminating observation (p. 414) that the difficulty in explaining the equity premium using this model stems from the need to use an implausibly high coefficient of relative risk aversion (CRRA). That is, the model fits the data well with a CRRA of 45, a plausible elasticity of intertemporal substitution and a plausible discount factor.

The present simplified model, which predicts a flexible degree of greater risk aversion to aggregate risks, then represents a promising avenue. A more general dynamic version of the present model should be calibrated on data for stocks and bonds. It would be worthwhile if it could ultimately contribute an element to any final resolution of the puzzle.

An important approach in the literature that addresses the equity premium puzzle involves the introduction of ambiguity—uncertainty about the underlying distribution of risks. The notion of ambiguity allows the individual to be averse to such higher-order uncertainty. That is, the individual may consider

[#]We are very grateful to Ken Kasa for constructing this for us. The bars are National Bureau of Economic Research-dated recessions. The ex ante equity premium is the fitted value from the regression of the 1-year ahead excess return on the current dividend yield, as in ref. 25. It has an average value of 6.8%.

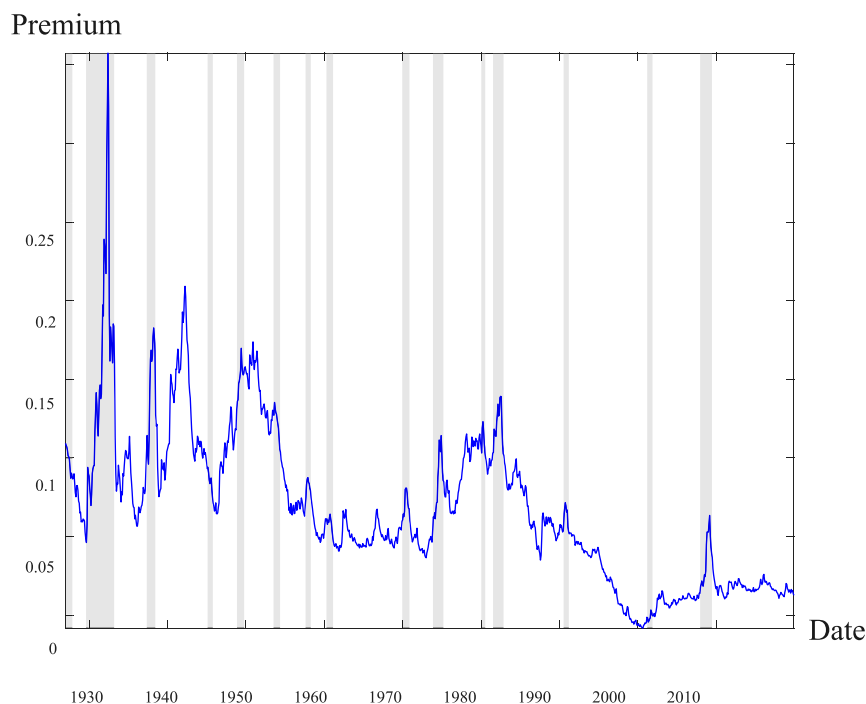


Fig. 1. US equity risk premium 1927 to 2019.

such a two-tiered structure as less desirable than the reduced form, one-tier risk obtained in a straightforward fashion by combining the probabilities from the two tiers.

A key paper that accounts for ambiguity aversion is ref. 30. The criterion proposed there is formally similar to the biological criterion discussed in *Evolved Attitudes to Aggregate and Idiosyncratic Risk*. The role played by aggregate risk here is played by ambiguity there, although the function \ln here is replaced by a more general concave function capturing the differential aversion to ambiguity. Aggregate risk and ambiguity may sometimes be difficult to distinguish empirically.^{||} To the extent this is so, the current biological approach could be viewed as providing a biological foundation for ambiguity aversion.

The model of ref. 31 permits independent specification of attitudes to risk, attitudes to ambiguity, and intertemporal inequality. (The recursive intertemporal model of ref. 32 also generalizes ref. 27 to allow for ambiguity aversion and ref. 30 to allow for intertemporal substitution.)

When this generalized model is applied to the equity premium puzzle, however, a high level of ambiguity aversion is still needed. (The parameter η in ref. 31 is an elasticity measuring ambiguity aversion and is estimated to be 8.86.) There is not much evidence on the level of ambiguity aversion in other contexts, but the plausibility of this resolution depends on such evidence also yielding comparably high estimates of ambiguity aversion.

A common feature of many resolutions of the equity premium puzzle is indeed that they raise issues concerning whether behavior outside the context of the stock market would be consistent with the estimated model, whether the resolution builds in a high level of ambiguity aversion, or a high level of risk aversion, with respect to stocks.**

^{||} Investors are often thought to prefer domestic stocks. In this case, the interpretation that international stocks have returns that are partly ambiguous seems more compelling, however, than the interpretation that international stocks have a larger aggregate or common component than domestic stocks.

** Ref. 33 also develops a model of intertemporal asset pricing that elaborates ref. 1. However, a fairly high coefficient of relative risk aversion (5 or 6) is still needed.

The partial resolution of the puzzle offered here argues that humans may have evolved to be more averse to the aggregate risk generated by stocks than to other idiosyncratic risk. Our argument holds even if individuals are aware, for example, of the distribution of persistent growth rates or of the extremes of the distribution of stock market collapses.

Present Contribution. The purpose of the present paper is to demonstrate how aggregate risk might entail an arbitrarily large degree of extra risk aversion relative to idiosyncratic risk. In a simple pedagogic atemporal setting, we show that an individual should have less exposure to stocks—where there is aggregate risk—than would be suggested by her attitudes to idiosyncratic risk (property loss, for example).

Indeed, under plausible assumptions on the function Ψ , the difference in the effect of the two types of risk on portfolio choice can be arbitrarily large. Hence, this can reconcile evidence of a coefficient of relative risk aversion near 1 when considering property loss, for example, with evidence of a coefficient of relative risk aversion that is an order of magnitude or more greater when considering exposure to the stock market.^{††} We further show that these results can be extended to a simple dynamic model that allows for intertemporal substitution. This simple model maintains an arbitrarily large gap between attitudes to aggregate and idiosyncratic risk but generates plausible elasticities of intertemporal substitution.

The Static Model

The Biological Production Function Ψ . The argument sketched above in *Evolved Attitudes to Aggregate and Idiosyncratic Risk* implies that the criterion that should evaluate aggregate risk is $E \ln \Psi$, where $E \Psi$ evaluates idiosyncratic risk. Since the function \ln is strictly concave, such a transformation produces

^{††} Recall that ref. 26, using US data on property and liability insurance, estimates that the coefficient of relative risk aversion is between 1.2 and 1.8. This sharply contrasts with ref. 29, for example, which observes that data on the stock market suggests the need for a much higher CRRA—perhaps 45.

unambiguously greater risk aversion, and this is a key element of the present argument. However, this extra risk aversion alone cannot resolve the equity premium puzzle. Suppose, for example, that $\Psi(x) = x^\gamma$ for $\gamma \in (0, 1)$. (It has to be that $\Psi \geq 0$ given the interpretation of Ψ as expected offspring.) In this case, $\ln \Psi(x) = \gamma \ln(x)$. The coefficient of relative risk aversion for Ψ is then $1 - \gamma$, whereas that for $\ln \Psi$ is $1 > 1 - \gamma$. Although this effect goes in the right direction, these are modest coefficients with a difference that is far too small in the context of the equity premium puzzle.

The second key element then needed for the present argument is defended above in *Convex-Concave Ψ in Biology and Economics*. This element is the assumption that the function Ψ has a shape inspired by production functions in economics. Such production functions Ψ would satisfy— Ψ is twice differentiable, with $\Psi(0) = 0$, $\Psi'(x) > 0$, for $x \geq 0$, and there exists $A > 0$ such that $\Psi''(x) > 0$, for $x \in [0, A)$ but $\Psi''(x) < 0$, for $x > A$.

This supposes that increasing x when it is low has an increasing marginal effect on expected offspring and it is only for larger values that a decreasing marginal effect is evident. This generalizes the idea that there is a threshold effect, so that there must be at least a minimum level of x to generate positive offspring.

Indeed, for simplicity and tractability, we directly assume such a threshold effect, as a limiting case of the general convex-concave function Ψ described above. We assume then there is a threshold $A > 0$ such that $\Psi(x) = 0$, $x \leq A$ but $\Psi'(x) > 0$, $\Psi''(x) < 0$, $x > A$. We assume Ψ is continuous. It is also differentiable except at $x = A$ (Fig. 2).

This threshold formulation is simple, but it seems that the results will be robust to the more general formulation, as long as Ψ is sufficiently close to zero initially.

Stocks Versus Bonds. Suppose bonds have certain return R , but the stock market is risky with returns $0 < r_1 < r_2 < \dots < r_S$ with probabilities $\pi_1 > 0, \dots, \pi_S > 0$, where $\sum_s \pi_s = 1$. This is aggregate risk. To avoid triviality, we suppose that $r_1 < R$ and $r_S > R$, as, otherwise, the optimal choice is obviously to invest only in stocks or only in bonds. Given the threshold formulation, we similarly assume that $RW > A$, so a portfolio invested only in bonds generates positive offspring. The investor has initial wealth $W > 0$ and puts a fraction α into the stock market, with $1 - \alpha$ in bonds.^{††}

Aggregate Risk. The threshold formulation implies that there exists an upper bound $\bar{\alpha}$ on the fraction of the portfolio in stocks. It must be that the worst outcome for the market yields strictly positive offspring given the criterion $\ln \Psi(x)$.^{§§}

This is because zero offspring is catastrophic as an aggregate outcome, reflected in $\ln(0) = -\infty$. On the other hand, although zero offspring is bad as an idiosyncratic outcome, it is not catastrophic. This yields an extreme form of the evolutionary preference for idiosyncratic risk over comparable aggregate risk.

That is, it must be that $\alpha r_1 W + (1 - \alpha)RW > A$, so that $\alpha < \frac{RW - A}{(R - r_1)W} = \bar{\alpha}$. The investor should solve

$$\max_{\alpha \in [0, \bar{\alpha}]} V(\alpha) = \sum_s \pi_s \ln \Psi(\alpha r_s W + (1 - \alpha)RW), \quad [2]$$

^{††} It will follow that the agent will not wish to short sell the risky asset by choosing $\alpha < 0$. On the other hand, she can borrow at rate R to finance additional stock market purchases and so can choose $\alpha > 1$. It is straightforward to analyze the model under the restriction that $\alpha \leq 1$. As long as it is assumed that $\alpha^A < 1$, then it still follows that $\alpha^A > \alpha^A$, although it may be that $\alpha^A = 1$ as a corner solution. The assumption that $\alpha^A < 1$ is realistic, especially in the light of the equity premium puzzle. However, if $\alpha^A = 1$ is allowed then the model would predict that $\alpha^A = 1 = \alpha^A$.

^{§§} Effectively, the criterion $\ln \Psi(x)$ implies a constraint analogous to limited liability on the individual. That is, it is effectively ruled out for the individual to have wealth less than or equal to A .

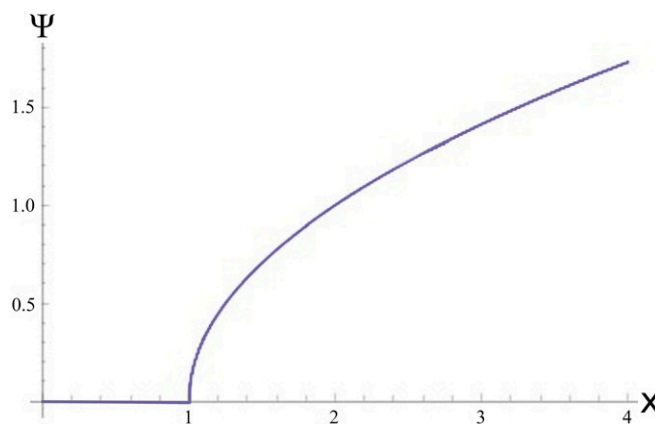


Fig. 2. Biological production function with $A = 1$.

which is strictly concave in $\alpha \in [0, \bar{\alpha}]$. We have

$$V'(\alpha) = \sum_s \frac{\pi_s (r_s - R) W \Psi'(\alpha r_s W + (1 - \alpha)RW)}{\Psi(\alpha r_s W + (1 - \alpha)RW)}. \quad [3]$$

It follows readily that $V'(0) > 0$ if and only if $\bar{r} > R$, where $\bar{r} = \sum_s \pi_s r_s$. That is, the investor chooses a strictly positive investment in the stock market if and only if the expected rate of return on the stock market exceeds that on the safe asset, bonds, which we assume to be true. (In a more general model, the price of the risky asset must be low enough to make the stock returns high enough, so that the risky asset is held.)

Suppose then that $\alpha^A \in (0, \bar{\alpha})$ is the optimum fraction of wealth that should be invested in the stock market given that the risk is aggregate. Since $V'(0) > 0$ and $V'(\bar{\alpha}) = -\infty$, α^A is the unique solution of

$$V'(\alpha) = \sum_s \frac{\pi_s (r_s - R) W \Psi'(\alpha r_s W + (1 - \alpha)RW)}{\Psi(\alpha r_s W + (1 - \alpha)RW)} = 0. \quad [4]$$

What does this imply about how the optimal $\alpha^A \in (0, \bar{\alpha})$ varies with W ? Since $\bar{\alpha} = \frac{RW - A}{(R - r_1)W} < 1$, then $\frac{d\bar{\alpha}}{dW} > 0$, so that increasing W allows the share of the risky asset to increase. An increase in α^A is then a plausible consequence.

The optimal α^A is directly characterized by the condition $V'(\alpha) = 0$. By a standard result, $\frac{d\alpha^A}{dW} > 0$ if the criterion $\ln \Psi$ exhibits decreasing relative risk aversion. The moving threshold makes this possibility more plausible.

If, for example, $\Psi(x) = (x - A)^\gamma$, for $x \geq A$, then $\ln \Psi(x) = \gamma(x - A)$ and the coefficient of relative risk aversion is $\frac{x}{x - A}$, which is decreasing in x for $x \geq A$.

We next show that, if the risk aversion of the individual is estimated in contexts with idiosyncratic risk, she will choose less exposure to the stock market—with its aggregate risk—than this risk aversion predicts.

Comparison with Idiosyncratic Risk. Consider the counterfactual thought experiment that the individual faces precisely the same portfolio choice problem but where her preferences are those derived from idiosyncratic risk. That is, suppose that Ψ has been estimated based on observations involving idiosyncratic risk (insurance against automobile accidents, for example). What would these estimated preferences imply about portfolio choice?

First, note that there is an upper bound to α in this situation as well. We assume that the individual can never attain negative

wealth, so that $\alpha r_1 W + (1 - \alpha)RW \geq 0$. Hence, $\alpha \leq \hat{\alpha} = \frac{R}{R - r_1}$, where $\hat{\alpha} > 1$ and $\hat{\alpha} > \bar{\alpha}$.

Suppose then the individual maximizes $\ln E\Psi$, or, equivalently, simply $E\Psi$. The individual would then solve

$$\max_{\alpha \in [0, \hat{\alpha}]} U(\alpha) = \sum_s \pi_s \Psi(\alpha r_s W + (1 - \alpha)RW). \quad [5]$$

Overall, U need not be concave, but it is concave on $[0, \bar{\alpha}]$.¹¹ It follows that

$$U'(\alpha) = \sum_s \pi_s (r_s - R) W \Psi'(\alpha r_s W + (1 - \alpha)RW) \quad [6]$$

and that $U'(0) > 0$ because we have assumed that $\bar{r} > R$.

Suppose then that $\alpha^I \in (0, \hat{\alpha}]$ is the fraction of wealth that would be invested in the stock market if the individual treats the risk there as idiosyncratic and maximizes $E\Psi$.

Proposition. Under the assumptions described above, $\alpha^I > \alpha^A$. That is, the fraction of wealth the individual would be incorrectly anticipated to invest in the stock market is strictly greater than the fraction that is optimal.

Proof: We show that $U'(\alpha^A) > 0$. To do this, recall that $0 < r_1 < r_2 < \dots < r_S$. Define

$$\bar{\pi}_s = \bar{k} \pi_s \frac{\Psi'(\alpha r_s W + (1 - \alpha)RW)}{\Psi(\alpha r_s W + (1 - \alpha)RW)} \quad [7]$$

and

$$\hat{\pi}_s = \hat{k} \pi_s \Psi'(\alpha r_s W + (1 - \alpha)RW), \quad [8]$$

where \hat{k} and \bar{k} are such that $\sum_s \hat{\pi}_s = \sum_s \bar{\pi}_s = 1$. Since $\Psi(\alpha r_s W + (1 - \alpha)RW)$ is increasing in s , it follows that the distribution given by the $\hat{\pi}_s$ first order stochastically dominates that given by the $\bar{\pi}_s$, so $\sum_s \bar{\pi}_s r_s < \sum_s \hat{\pi}_s r_s$. At $\alpha = \alpha^A$, we have

$$V'(\alpha^A) = \left(\sum_s \bar{\pi}_s r_s - R \right) W = 0, \quad [9]$$

so that

$$U'(\alpha^A) = \left(\sum_s \hat{\pi}_s r_s - R \right) W > 0. \quad [10]$$

If $\alpha^I \geq \bar{\alpha}$, then $\alpha^I > \alpha^A$, because $\bar{\alpha} > \alpha^A$. Otherwise, if $\alpha^I < \bar{\alpha}$, then $\alpha^I > \alpha^A$ follows from the concavity of U on $[0, \bar{\alpha}]$ and $U'(\alpha^A) > 0$. This completes the proof.

Furthermore, α^A can display an arbitrarily high degree of risk aversion relative to α^I , in the present context, as we show below in *Arbitrarily High Aversion to Aggregate Risk*.

Arbitrarily High Aversion to Aggregate Risk. Suppose, for simplicity, that $S = 2$, where $r_1 < R$ has probability $\pi > 0$ and $r_2 > R$ has probability $1 - \pi > 0$. We have $\pi r_1 + (1 - \pi)r_2 = \bar{r} > R$ and $RW > A$.

It must be true that $\alpha^A < \bar{\alpha}$ regardless of π and r_2 . However, this contrasts with the observation that α^I will attain its upper bound if π is small enough. Consider then the value of $\alpha^I > \alpha^A$.

Whenever $\alpha > \bar{\alpha}$, then $\Psi(\alpha r_1 W + (1 - \alpha)RW) = 0$, so that $U(\alpha) = (1 - \pi)\Psi(\alpha r_2 W + (1 - \alpha)RW)$, which is increasing (and concave) in α since $r_2 > R$. This is because increasing α has

no downside in this range. It follows that $\alpha = \hat{\alpha}$ is the best choice of α in $[\bar{\alpha}, \hat{\alpha}]$.

If, on the other hand, $\alpha < \bar{\alpha}$, then U is concave on $[0, \bar{\alpha}]$ and

$$U'(\alpha) = \pi(r_1 - R)W\Psi'(\alpha r_1 W + (1 - \alpha)RW) + (1 - \pi)(r_2 - R)W\Psi'(\alpha r_2 W + (1 - \alpha)RW). \quad [11]$$

It is clear that $\lim_{\alpha \uparrow \bar{\alpha}} U'(\alpha) > 0$ whenever $\pi > 0$ is small enough, so that the concavity of U implies that $\bar{\alpha}$ is the best choice in $[0, \bar{\alpha}]$.

Altogether, then, it follows that $\alpha^I = \hat{\alpha}$, whenever $\pi > 0$ is small enough (Fig. 3).

Hence, when $\pi > 0$ is small enough, although the optimal share, α^A in stocks is bounded by $\bar{\alpha} < \hat{\alpha}$, where $\bar{\alpha}$ is independent of π , it nevertheless follows that $\alpha^I = \hat{\alpha}$.

Proposition. Under the assumptions given for the example described above, $\alpha^A < \bar{\alpha}$ but $\alpha^I = \hat{\alpha} > \bar{\alpha}$, whenever π is sufficiently small. That is, the fraction of wealth that the individual would be incorrectly anticipated to invest in the stock market is maximal if π is small enough. Nevertheless, the optimal fraction may be bounded well below this maximal level.

Hence, the portfolio choice that would be anticipated based on observed choice under idiosyncratic risk (using Ψ) differs significantly from the portfolio choice that is evolutionarily appropriate for aggregate risk (using $\ln \Psi$).

The bound on α^A derived here for the utility $\ln \Psi$ does not arise with conventional utility, no matter how risk-averse this might be. Suppose, for example, that the utility used to evaluate portfolio choice has constant coefficient of relative risk aversion greater than 1 and so is of the form $v(x) = -x^{-\gamma}$, for $\gamma > 0$, and all $x \geq 0$. Then, no matter how large the fixed value of γ might be, in the limit as $\pi \rightarrow 0$, any such utility must eventually put maximal wealth into the stock market.

These results will be less stark for a general convex-concave Ψ function, but they seem bound to still hold qualitatively if Ψ is close to zero initially.

Endogenous Static Risk Free Rate. Many theoretical discussions of the equity premium puzzle are based on the Lucas tree model from ref. 34. The stock market is the economy and generates random dividends, as fruit falling from a tree. There is no actual technology that permits risk-free investment, but a risk-free asset can be constructed and priced. The price of this asset must then adjust to clear the market at zero. (See ref. 29, for example.) The implied risk-free rate is then such that the representative agent chooses to hold only the risky stock market asset. This risk-free

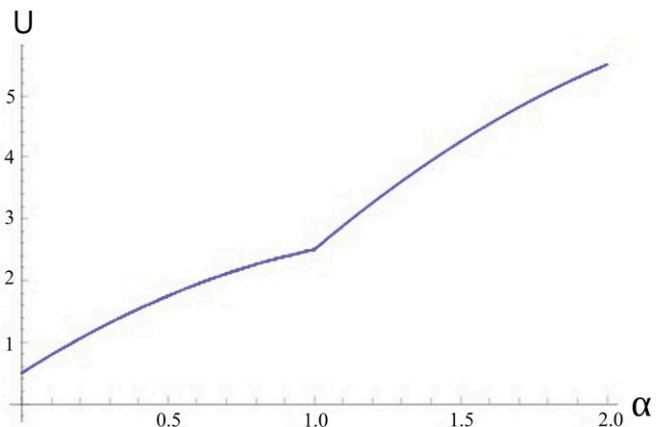


Fig. 3. The function $U(\alpha)$ with $\bar{\alpha} = 1$ and $\hat{\alpha} = 2$, when $U'(1) > 0$.

¹¹ Such nonconcave U may generate risk-taking behavior over gambles with zero off-spring as one possibility. This possibility does not arise with the criterion $\ln \Psi$, as discussed in *Aggregate Risk*. The shape of $U(\alpha)$ is illustrated in Fig. 3 for the case that $S = 2$ and where $\alpha^I = \hat{\alpha}$.

rate is too low, which is the flip side of the amount invested in stocks being too low in this static model.

With aggregate risk, it must be that $\bar{\alpha} > 1$, since, otherwise, $\alpha^A < 1$. Since $\alpha^A = 1$, then

$$V'(1) = \sum_s \frac{\pi_s(r_s - R)W\Psi'(r_s W)}{\Psi(r_s W)} = 0, \quad [12]$$

characterizing \bar{R} , say, as $\bar{R} = \sum_s \bar{\pi}_s r_s$ for $\bar{\pi}_s = \bar{k} \pi_s \frac{\Psi'(r_s W)}{\Psi(r_s W)}$, where \bar{k} is such that $\sum_s \bar{\pi}_s = 1$.

For idiosyncratic risk, we have $\hat{\alpha} > \bar{\alpha} > 1$. Then $\alpha^I = 1$ implies

$$U'(1) = \sum_s \pi_s(r_s - R)W\Psi'(r_s W) = 0, \quad [13]$$

which characterizes \hat{R} , say, as $\hat{R} = \sum_s \hat{\pi}_s r_s$ for $\hat{\pi}_s = \hat{k} \pi_s \Psi'(r_s W)$, where \hat{k} is such that $\sum_s \hat{\pi}_s = 1$.

The distribution given by the $\hat{\pi}_s$ first-order stochastically dominates that given by the $\bar{\pi}_s$ since $\Psi(r_s W)$ is increasing in s . We have shown then that $\hat{R} > \bar{R}$, so the observed risk-free rate is too low—lower than the rate anticipated on the basis of projecting estimated preferences over idiosyncratic gambles to the stock market. That is:

Proposition. *Under the assumptions described above, $\hat{R} > \bar{R}$. The observed risk-free rate, \bar{R} , is too low, that is, lower than the rate, \hat{R} , anticipated on the basis of projecting estimated preferences over idiosyncratic gambles to the stock market.*

A full discussion of the equity premium puzzle requires a dynamic model in which explicit intertemporal tradeoffs are possible. This because investment in stocks fundamentally involves tradeoffs over time that the above static model abstracts away from.

A Simple Dynamic Model

It is important then to develop a more general biological model in which intertemporal tradeoffs are possible, but the effects of idiosyncratic and aggregate risk can still be compared. This more general model maintains the assumption that there is no density dependence. The results will fit the template described in ref. 29 (p. 414) of extremely high aversion to stock market risk but a plausible elasticity of intertemporal substitution and (implicitly but crucially) plausible attitudes to other risks.

The analysis of a general age-structured evolutionary model incorporating aggregate risk is complex, as illustrated in ref. 3. This will be the focus of future research. (Another interesting angle would be to consider the implications of “bet-hedging” [as in ref. 6] in this context.) To demonstrate the potential of the biological approach for the present purpose, we confine attention to the simplest possible case with just two adult age classes.

Individuals are born at age $a=0$, survive to age $a=1$ with probability $\delta_0 \in (0, 1)$, producing $\Psi(x_1)$ expected offspring at $a=1$. They then survive to age $a=2$ with probability $\delta_1 \in (0, 1)$, producing $\Psi(x_2)$ expected offspring at $a=2$. Here, x_a represents economic resources available at age $a=1, 2$, respectively, and Ψ is the biological production function described above in *The Biological Production Function* for the static model. This function plays the role of utility for situations lacking aggregate risk; for simplicity, the function is assumed to be age-invariant.

Suppose the x_a are constant, again for simplicity, and consider the evolution of the age-structured population in discrete time. This system is deterministic assuming the population is large and is given as

$$N(t+1) = N(t)L \text{ where } N(t) = (N_1(t), N_2(t))$$

is the row vector describing the age-structured adult population at date $t=0, 1, \dots$ and $L = \begin{bmatrix} \delta_0 \Psi \delta_1 \\ \delta_0 \Psi 0 \end{bmatrix}$ is the “Leslie matrix.” It is a consequence of the Perron–Frobenius Theorem that the population settles down into steady-state growth where the age structure of the population is constant, so that $N(t+1) = \lambda N(t)$, for some $\lambda > 0$. This limiting growth factor is the unique positive solution for λ of the Euler–Lotka equation (2) (λ is the dominant eigenvalue of L):

$$1 = \frac{\delta_0 \Psi(x_1)}{\lambda} + \frac{\delta_0 \delta_1 \Psi(x_2)}{\lambda^2}. \quad [14]$$

Idiosyncratic risk at $a=1$, at $a=2$, or both is evaluated by taking the expectation of Ψ ; indeed, the definition of Ψ builds in an expectation already.

The criterion $\Psi(x_1) + \frac{\delta_1 \Psi(x_2)}{\lambda}$ ties together attitudes to intertemporal choice and attitudes to idiosyncratic risk in the standard fashion. (If λ is maximal, then this criterion must be maximized given that value of λ [see ref. 2].) For example, if $\Psi(x) = (x - A)^\gamma$, for $x \geq A$ and $\gamma \in (0, 1)$, the elasticity of intertemporal substitution is $\frac{x-A}{(1-\gamma)x} \rightarrow \frac{1}{1-\gamma} \in (1, \infty)$ as $x \rightarrow \infty$.

Crucially, we now show that attitudes to aggregate risk are nonstandard, and there can be arbitrarily greater aversion to aggregate risk than to idiosyncratic risk. (This separation induced between attitudes to intertemporal choice and aggregate risk is achieved in a fashion that is unrelated to ref. 27, which separates attitudes to intertemporal choice and all forms of risk.)

As a minor simplification, suppose that $\delta_0 = \delta_1 = \delta$. More importantly, suppose $x_1 = x_2$, and there are two realizations of this common value: x^1 and x^2 , arising in states 1 and 2, respectively. Suppose the state is revised independently in periods $0, \tau, 2\tau, \dots$, for $\tau > 0$. If it is revised, it becomes state 1 with probability π and state 2 with probability $1 - \pi$. We consider the limit as $\tau \rightarrow \infty$.

Suppose that λ^i is the solution of the Euler–Lotka Eq. 14 for $x_1 = x_2 = x^i$, for $i=1, 2$. The effect of the infrequent transition is that the population will usually be in steady state growth. That is, the substantial complications introduced by the transitions from one regime to the other have only a small effect. (Without this assumption, the problem involves characterizing the growth rate of a random product of Leslie matrices, which is a difficult problem to analyze.)

More precisely, consider the total population, $P(T)$, say, at date $T = \bar{n}\tau = (\bar{n}_1 + \bar{n}_2)\tau$, where \bar{n}_i is the number of occurrences of regime $i=1, 2$, and $\bar{n}_1 + \bar{n}_2 = \bar{n}$. If $P(0) = 1$, which is without loss of generality, then

$$\frac{1}{T} \ln P(T) = \frac{1}{T} \sum_{n \in S_1} \ln \frac{P((n+1)\tau)}{P(n\tau)} + \frac{1}{T} \sum_{n \in S_2} \ln \frac{P((n+1)\tau)}{P(n\tau)}, \quad [15]$$

where S_i is the subset of the integers $\{0, \dots, \bar{n}-1\}$ such that $n \in S_i$ if and only if state $i=1, 2$ is drawn in period $n\tau$.

Fix any $\varepsilon > 0$, and choose τ large enough that

$$\frac{1}{\tau} \ln \frac{P((n+1)\tau)}{P(n\tau)} \in [\ln \lambda^i - \varepsilon, \ln \lambda^i + \varepsilon] \quad [16]$$

for all $n \in S_i$, for $i=1$, and for $i=2$. [This can be done uniformly in the age distribution in $P(n\tau)$; see ref. 35.] For such τ , it follows that

$$\left| \frac{1}{T} \ln P(T) - (f_1 \ln \lambda^1 + f_2 \ln \lambda^2) \right| \leq \varepsilon, \quad [17]$$

where $f_i = \frac{\bar{n}_i}{\bar{n}}$, $i=1, 2$. Since $(f_1, f_2) \rightarrow (\pi, 1 - \pi)$, as $\bar{n} \rightarrow \infty$, with probability 1, the long-run growth rate of the population can be made arbitrarily close to $\pi \ln \lambda^1 + (1 - \pi) \ln \lambda^2$, by choosing

ε small enough (and hence τ large enough). Evolutionary success is then measured by the criterion $E \ln \lambda$. (See ref. 15 for a rigorous analysis of a more general continuous-time model.)

Since the population is generally close to steady-state growth at rate $\ln \lambda^1$ or $\ln \lambda^2$, the observations made already concerning the elasticity of intertemporal substitution remain valid. The appropriate utility is always Ψ ; higher values of λ merely imply a higher factor representing the pure rate of time preference, λ/δ .

The effect of aggregate risk involves how λ depends on offspring Ψ . Using the quadratic formula to solve the Euler-Lotka equation for the (unique) positive root of λ yields $\lambda = \frac{\Psi + \sqrt{\Psi^2 + 4\Psi}}{2} \delta$. Hence, $\frac{d\lambda}{d\Psi} = \frac{1 + (\Psi^2 + 4\Psi)^{-1/2}(\Psi + 2)}{2} \delta > 0$, so that $\frac{d^2\lambda}{d\Psi^2} = -\frac{2\delta}{(\Psi^2 + 4\Psi)^{3/2}} < 0$. Thus, $\lambda(\Psi)$ is an increasing concave function.

Aggregate risk is evaluated by the criterion $E \ln \lambda(\Psi(x))$. Since $\lambda(0) = 0$, the results of the static model carry over to this dynamic case. That is, $\lambda(\Psi(x)) = 0$ for $x \leq A$ and $\lambda(\Psi(x))$ is concave for $x \geq A$. The concavity of λ implies that there is indeed more risk aversion for aggregate risk relative to idiosyncratic risk in this dynamic model than there was in the static case.##

More generally, suppose that Ψ_a are expected offspring at ages $a = 1, 2$. If $\delta_0 = \delta_1 = \delta$, the Euler-Lotka equation is $1 = \delta\Psi_1/\lambda + \delta^2\Psi_2/\lambda^2$. The positive solution is now $\lambda = \delta(\Psi_1 + \sqrt{\Psi_1^2 + 4\Psi_2})/2$. It follows readily that λ is an increasing concave function of Ψ_2 alone. Interestingly, however, λ is an increasing convex function of Ψ_1 . Hence, younger adults are then less averse to aggregate risk than are older adults. This is special case of a result for a continuum of ages in ref. 15, which suggests a biological explanation for the observed tendency of older individuals to move out of the stock market—a tendency that is awkward to explain with conventional preferences.

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Crucially, the elasticity of intertemporal substitution is that derived from the criterion that assesses idiosyncratic risk, $\Psi(x)$, and this does not entail implausibly low values.

Conclusion

We investigate the implications of a biological approach to risk attitudes by considering the implications for portfolio choice. In a static model, an individual chooses less exposure to the stock market—with aggregate risk—than would be implied by her attitudes to idiosyncratic risk. Alternatively, if the risk-free rate is endogenously set to clear the market for the safe asset at zero, the observed risk-free rate is lower than would be implied by her attitudes to idiosyncratic risk. Furthermore, the difference can be large enough to account for the equity premium puzzle.

We sketch how these results could arise in a more general dynamic model. In an example where there are two adult ages, there can also be a large difference between attitudes to aggregate and idiosyncratic risk, while the elasticity of intertemporal substitution remains plausibly high.

Data Availability. Data for Fig. 1 are available online from ref. 36.

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