

Sustainability in a Risky World

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How much consumption is sustainable, if “sustainability” requires that welfare should not be expected to decline over time? We impose a sustainability constraint on a standard consumption/portfolio choice problem. The constraint does not distort portfolio choice, but it imposes an upper bound on the sustainable consumption-wealth ratio, which must lie between the riskless interest rate and the expected return on wealth (and if risky capital evolves according to a geometric Brownian motion, it lies exactly halfway between the two). Sustainability requires an upward drift in wealth and consumption to compensate future generations for the increased risk they face.

Do ethical considerations restrict the rate at which society consumes, or its preference for the present over the future? Economists have answered this question in different ways.

One view is that preferences, social or individual, must be taken as given. If society discounts the future at a high rate, strongly preferring present consumption over future consumption, that preference must be respected; and if it leads to high consumption today, declining over time, that outcome must be accepted.

An alternative view, famously expressed by Ramsey (1928), is that at least for long-term discounting over the lifetimes of multiple generations, society should not discount the future at all because to do so is unethically to privilege the generation alive today over those yet unborn. Recently, this view has found powerful expression in the *Stern Review* (Stern, 2006), which argues for aggressive action to combat climate change in large part on the basis of a social rate of time preference close to zero.

A third view is that social choices over consumption and saving should be subjected to an external “sustainability” constraint. Sustainability was defined by the World Commission on Environment and Development (1987) as a consumption plan that “meets the needs of the present without compromising the ability of future generations to meet their own needs.” Economists including Pezzey (1992), Solow (1993), Howarth (1995), Arrow et al. (2004), Asheim (2007), and Llavador et al. (2015) have formalized this as a requirement that social value—the expected discounted value of utility from the present to the infinite future—should

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not decline over time. In the words of Solow (1993),

A sustainable national economy is one that allows every future generation the option of being as well off as its predecessors. The duty imposed by sustainability is to bequeath to posterity not any particular thing ... but rather to endow them with whatever it takes to achieve a standard of living at least as good as our own and to look after their next generation similarly.

The concept of sustainability as a constraint, rather than an objective, is consistent with the moral philosophy of Rawls (1999).¹ It can be understood as a prior principle that an ethical society should impose on itself because it would be agreed to by an individual who does not know into which of a sequence of generations they will be born. Since the time of birth is “morally arbitrary”, it should not influence expected utility.

As Arrow et al. (2004) discuss, in a deterministic economy with a single form of capital that has a constant riskless rate of return the sustainability constraint requires that the social rate of time preference does not exceed the exogenous riskless interest rate. When the constraint binds, the constrained rate of time preference equals the riskless interest rate, implying that society consumes the riskless return generated by its wealth and leaves the capital stock unchanged. Wealth, consumption, the utility and marginal utility of current consumption, and social value are then all constant over time. Sustainable consumption is only feasible when the riskless interest rate is positive. When it is, the sustainability constraint responds to the availability of an investment opportunity with a positive rate of return by allowing a greater rate of time preference and higher current consumption than would be required by Ramsey.²

In this paper we extend the concept of sustainability to allow for risk. In a risky economy, with an uncertain return on capital, it is not possible to guarantee that social value remains constant over time. Instead, we impose a weaker sustainability constraint that social value—expected utility, which is itself a random variable because it is a function of current wealth—should not be *expected* to decline over

¹Rawls (1999, §6) writes, “In justice as fairness, on the other hand, persons accept in advance a principle of equal liberty and they do this without knowledge of their more particular ends. They implicitly agree, therefore, to conform their conceptions of the good to what the principles of justice require, or at least not to press claims which directly violate them. ... The principles of right, and so of justice, put limits on which satisfactions have value; they impose restrictions on what are reasonable conceptions of one’s good. In drawing up plans and deciding on aspirations men are to take these constraints into account.”

²By adjusting the rate of time preference to available rates of return, the sustainability constraint responds to a critique of Ramsey made by Koopmans (1960, 1967). Koopmans (1967) summarized his argument by writing: “The moral is, in my opinion, that one cannot adopt ethical principles without regard to ... the anticipated technological possibilities. Any proposed optimality criterion needs to be subjected to a mathematical screening, to determine whether it does indeed bear on the problem at hand, under the circumstances assumed. More specifically, too much weight given to generations far in the future turns out to be self-defeating. It does nobody any good. How much weight is too much has to be determined in each case.”

time. This constraint, which has also been suggested though not formally analyzed by Howarth (1995), acknowledges the reality that social welfare is subject to random shocks, some of which cannot be controlled. In the deterministic case, our constraint reduces to the one considered by Arrow et al. (2004).

We study a continuous-time model with two forms of capital, one safe and one risky, so that society faces an asset allocation problem as well as a consumption-savings decision. While we use the terminology of financial economics—referring, for example, to assets, wealth, consumption, and saving—we emphasize two ways in which these financial concepts should be interpreted broadly.

First, the assets we discuss are forms of capital that can be accumulated under constant returns to scale. Our model is a two-capital extension of a standard endogenous growth or Ak model such as Romer (1986) or more recently Barro (2023). We also consider a version of the model in which only a single form of risky capital is physically available, so risk is inescapable for society. In this case riskless capital is in zero net supply and the riskless interest rate adjusts to ensure zero net demand for riskless investment. This version of the model is standard in the endogenous growth literature.

Second, the financial concepts we use should be interpreted to include not only the standard objects measured in national income accounts, but also other conditions relevant for human well-being and productivity including particularly environmental conditions. The risky asset, for example, could represent the Earth itself, while consumption should be understood as a catch-all for, among other things, the rate at which society consumes, rather than sustains, the biosphere. In these terms, the consumption-savings decision we consider is intended as a modelling metaphor that encompasses questions of resource depletion, environmental degradation, and so on. Having said that, we should be clear that our framework does not address certain important aspects of environmental sustainability, notably issues related to the economics of exhaustible resources (as studied in a deterministic setting by Dasgupta and Heal (1974), Solow (1974), and Hartwick (1977)).

Returning to the financial terminology we use in the remainder of the paper, we assume that the returns on the risky asset are i.i.d., with a flexible specification that is driven both by a Brownian motion and by a Poisson jump process. The assumption of i.i.d. returns is consistent with an Ak model of capital accumulation. It implies that there is a unique consumption-wealth ratio at which the sustainability constraint is binding.³ By allowing for jumps, we accommodate the literature that emphasizes the importance of rare disasters, or fat tails more generally, in the macroeconomy (Rietz 1988, Barro 2006, Weitzman 2007a, Backus, Chernov and Martin 2011). We assume that society has a time-separable power utility function defined over aggregate consumption, and we impose the sustainability constraint on this.

³In a model with diminishing returns to capital, by contrast, any constant savings rate can be sustainable although different savings rates imply different levels of steady-state consumption.

Our main results are as follows.

First, when the sustainability constraint binds, the sustainable consumption-wealth ratio equals the certainty-equivalent return: the hypothetical riskless rate of return that would deliver the same expected utility to society as the actual menu of available assets. This depends on the risk aversion but not on the rate of time preference of an unconstrained representative individual in our economy.⁴

Second, the sustainability constraint does not distort portfolio choice, which is always the same whether or not the constraint binds. In the absence of jumps, the portfolio rule is the classic one derived by Merton (1969, 1971).

Third, the sustainable consumption-wealth ratio exceeds the riskless interest rate but is less than the expected return on optimally invested wealth. In the absence of jumps, the sustainable consumption-wealth ratio lies exactly at the midpoint between these two rates of return. In the presence of jumps of deterministic size, the sustainable consumption-wealth ratio is higher than the midpoint when the jumps are downward, that is, when jumps represent bad news.

Fourth, sustainability does not require that consumption and wealth are expected to remain constant over time. In fact, consumption and wealth have positive drift in the constrained equilibrium. Intuitively, this is because risky investment causes the distribution of consumption and wealth to spread out over time, imposing more risk on later generations. To prevent risk from reducing the welfare of later generations relative to earlier ones, later generations must be compensated by higher average levels of consumption and wealth.

Fifth, the sustainable consumption-wealth ratio is higher (by a factor of risk aversion divided by risk aversion minus one) than the consumption-wealth ratio required by the Ramsey zero-time-preference rule. The difference between the two is small for very high levels of risk aversion, but substantial at levels of risk aversion normally considered plausible.

The sustainable rate of time preference is not the same as the discount rate that society should apply to riskless investment projects. That discount rate is given by the riskless interest rate in the sustainable equilibrium, which is lower than the sustainable rate of time preference when the economy is exposed to risk. As a salient example, investments to mitigate climate change should be discounted at low rates if the investments are riskless and the sustainable equilibrium has a low riskless interest rate. They should be discounted at even lower rates if climate investments pay off in bad states of the world—that is, if they are analogous to insurance policies—an important point emphasized by Weitzman (2009) and Gollier (2021).

Our main analysis defines utility over aggregate consumption, in effect treating

⁴This is consistent with the view of Rawls (1999, §45), who writes: “Of course, a present or near future advantage may be counted more heavily on account of its greater certainty or probability . . . But none of these things justifies our preferring a lesser present to a greater future good simply because of its nearer temporal position . . . The just savings principle for society must not, then, be affected by pure time preference, since as before the different temporal position of persons and generations does not in itself justify treating them differently.”

each generation equally regardless of population. This is only equivalent to treating each individual equally if population is constant over time. Population growth creates notoriously difficult issues for intertemporal ethics (Parfit 1984, Dasgupta 2001), particularly when population is itself a choice variable. However we show in an online appendix that if population growth is exogenous and constant, then we can modify the sustainability constraint to prevent the expected utility of an individual from declining over time. This is equivalent to subtracting the rate of population growth from all rates of return, and therefore from the sustainable consumption-wealth ratio and the sustainable rate of time preference.

The literature on discounting and sustainability is enormous, and we do not attempt a complete review here. Dasgupta (2008, 2021) and Zeckhauser and Viscusi (2008) provide recent surveys. Within the literature on climate change, there has been debate between those such as Cline (1992) and Stern (2006, 2016) who argue for a very low social rate of time preference, and Nordhaus (1994) who uses a higher rate of time preference. Our analysis implies that a substantial rate of time preference can be consistent with the ethical criterion of sustainability in a risky world.

The organization of the paper is as follows. Section 1 sets up our unconstrained continuous-time model with portfolio choice over a safe and a risky asset. Section 2 introduces the sustainability constraint and solves the constrained model. Section 3 compares the sustainable consumption-wealth ratio with the consumption-wealth ratio implied by the Ramsey rule of a zero social rate of time preference. Section 4 concludes. When not included in the main text, proofs of results are in the appendix.

I. Unconstrained Consumption and Portfolio Choice

We consider a representative agent faced with two assets or technologies, one riskless and one risky. The agent chooses society's aggregate consumption, C_t , and risky portfolio share, α , to maximize the expected discounted value of a power utility function,

$$(1) \quad U_0 = E_0 \int_0^\infty e^{-\rho t} \frac{C_t^{1-\gamma}}{1-\gamma} dt.$$

We take as given this representation of utility derived from aggregate consumption. It can be derived from individual utility of individual consumption under assumptions that permit aggregation across consumers. For example, we could assume that individuals have a constant probability of death following Blanchard (1985), that they have power utility defined over their own consumption, that they are unable to annuitize their wealth, and that the wealth of those who die is allocated to an equal number of newly born individuals. In this case utility at each point of time is both the welfare of the generation born at that moment and the welfare of all agents alive at that time. This microfoundation for equation

(1) assumes a constant population; we discuss the impact of population growth further in the online appendix.

We assume that the rate of time preference $\rho > 0$. If individuals have a constant probability of death and do not care about their descendants, then as Blanchard (1985) shows, ρ is the sum of the pure individual rate of time preference and the probability of death. In a more general model with intergenerational altruism, ρ will also be affected by (and declining in) the degree of altruism.

We assume that the coefficient of relative risk aversion $\gamma > 1$. In the appendix, we show that our main Results 1 and 2 extend in the expected way to the log utility case, $\gamma = 1$. It would also be easy to handle the case $0 < \gamma < 1$, but as this case requires occasional sign flips in our logic below, we rule it out to streamline the exposition.

The riskless asset has gross return R_f . It will generally be convenient to think in terms of the log riskless rate, $r_f = \log R_f$.

We require assumptions about the return on wealth that is invested rather than consumed. It will be convenient to work in continuous time for tractability. As sustainability is inherently a long-run issue, we abstract away from high frequency variation in mean, volatility, and so on by modelling the risky return as i.i.d. over time (that is, as a Lévy process), as in Martin (2013). We specialize slightly, within this class of processes, by specifying the risky asset's value using a combination of a Brownian motion and a Poisson process. This is a more general assumption than it may appear: as we allow for an arbitrary jump size distribution, the only cases we are ruling out, within the family of Lévy processes, are those in which infinitely many jumps can occur in a finite time interval.

We assume that the risky asset has constant expected excess return $\mu = \log(ER/R_f) > 0$, Brownian volatility σ , and is exposed to jumps arriving according to a Poisson counting process N_t with constant arrival rate ω , where μ , σ , and ω are each constant. We write W_t for wealth at time t and $\theta = C_t/W_t$ for the consumption-wealth ratio. Under our assumptions, θ is also constant. Thus

$$(2) \quad \frac{dC_t}{C_t} = \frac{dW_t}{W_t} = \left[r_f + \alpha \underbrace{(\mu + \omega EL)}_{\hat{\mu}} - \theta \right] dt + \alpha \sigma dZ_t - \alpha L dN_t.$$

(In what follows we will often suppress time subscripts on the random variables C_t , W_t , Z_t and N_t to streamline the notation.)

Jumps are captured by the third term on the right-hand side of equation (2). When a jump occurs, an agent who is fully invested in the risky asset loses a fraction L of her capital. We assume that L is a random variable that is drawn in i.i.d. fashion each time a jump occurs. We also assume (with one eye on an equilibrium we study below, in which $\alpha = 1$) that L is strictly less than 1, so that someone who invests fully in the risky asset is not bankrupted. We can allow L to take negative values; these represent good news for the risky asset. We write $\hat{\mu} = \mu + \omega EL$ to denote the expected excess return in the absence of jumps.

It follows that

$$(3) \quad E C_t^{1-\gamma} = W_0^{1-\gamma} \theta^{1-\gamma} \exp \left\{ (1-\gamma) \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \gamma \alpha^2 \sigma^2 - \theta \right) t + \omega E \left[(1-\alpha L)^{1-\gamma} - 1 \right] t \right\}.$$

This is a standard calculation, but we provide details in the appendix for convenience. Hence the objective function (1) can be evaluated explicitly as

$$(4) \quad U_0 = \frac{W_0^{1-\gamma}}{1-\gamma} \frac{\theta^{1-\gamma}}{\rho - (1-\gamma) \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \gamma \alpha^2 \sigma^2 - \theta \right) - \omega E \left[(1-\alpha L)^{1-\gamma} - 1 \right]}.$$

The unconstrained optimal investment and consumption choices are identified by maximizing (4) with respect to α and θ . Maximizing with respect to θ , we find that the unconstrained optimal consumption-wealth ratio, θ_{unc} , is

$$(5) \quad \theta_{\text{unc}} = \frac{\rho + (\gamma - 1) \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \gamma \alpha^2 \sigma^2 \right) - \omega E \left[(1-\alpha L)^{1-\gamma} - 1 \right]}{\gamma}.$$

We assume that θ_{unc} is positive. This condition implies that the denominator of (4) is positive. If it does not hold, then the integral in the definition of expected utility does not converge, and expected utility is not well defined.

The optimal risky portfolio share is defined implicitly by

$$(6) \quad \hat{\mu} - \alpha \gamma \sigma^2 = \omega E \left[L (1 - \alpha L)^{-\gamma} \right].$$

In the absence of jumps, where the risky asset follows a pure Brownian motion, this simplifies to the classic Merton formula,

$$(7) \quad \alpha = \frac{\mu}{\gamma \sigma^2}.$$

The certainty-equivalent return

These equations can be simplified by introducing the concept of the certainty-equivalent return, r_{CE} , defined as the hypothetical riskless return that would give the investor the same expected utility as the actual menu of assets, conditional on the investor's choice of α and θ . Equation (4) shows that

$$(8) \quad r_{\text{CE}} = r_f + \alpha \hat{\mu} - \frac{1}{2} \gamma \alpha^2 \sigma^2 + \frac{\omega E \left[(1 - \alpha L)^{1-\gamma} - 1 \right]}{1 - \gamma},$$

which depends on risk aversion γ (both directly and indirectly through the effect of γ on the risky portfolio share α) but not on the rate of time preference ρ .⁵

⁵Although α , which appears in equation (8), is an equilibrium object, Result 2 shows that it does

Using this notation, the objective function in equation (4) can be rewritten as

$$(9) \quad U_0 = \frac{W_0^{1-\gamma}}{1-\gamma} \frac{\theta^{1-\gamma}}{\rho - (1-\gamma)(r_{CE} - \theta)},$$

and the solution for the unconstrained optimal consumption-wealth ratio can be simplified to

$$(10) \quad \theta_{\text{unc}} = \frac{1}{\gamma} \rho + \left(1 - \frac{1}{\gamma}\right) r_{CE}.$$

The unconstrained optimal consumption-wealth ratio is a weighted average of the rate of time preference ρ and the certainty-equivalent return r_{CE} , where the weights are risk tolerance and one minus risk tolerance.

II. A Sustainability Constraint

We formalize the notion of sustainability by imagining representatives of each generation agreeing on a time-invariant consumption-investment policy that respects a constraint that welfare should not be expected to decline over time. In doing so, we are committing to a cardinal measure of utility, as in Harsanyi (1955), that permits welfare comparisons to be made across generations.

This implies that at time t the representative agent will solve the consumption-investment problem studied above, subject to the extra constraint that the drift of expected utility should be nonnegative. If the representative agent is thought of as the currently living generation in an infinite dynasty, then the constraint is appropriate if she does not want her descendants to expect a lower quality of life than she does.⁶

Result 1. *The largest possible sustainable consumption-wealth ratio, θ_{con} , satisfies*

$$(11) \quad \theta_{\text{con}} = r_{CE},$$

where r_{CE} is defined in equation (8). *Unlike the unconstrained consumption-wealth ratio, the sustainable consumption-wealth ratio is independent of ρ if the constraint binds.*

PROOF:

not depend on ρ .

⁶One might imagine imposing other types of constraint. We could, for example, allow for a type of risk aversion over future expected utility by requiring that some concave function of future expected utility should have non-decreasing expectation. This is analytically intractable in the constant relative risk aversion (power) case, however; and indeed it is infeasible in the limit as risk aversion over future expected utility approaches infinity, as it would require expected utility—and hence wealth itself—to be non-decreasing, which is not possible unless society can entirely eliminate risk.

Equation (4) shows that expected utility at time t , U_t , is proportional to $W_t^{1-\gamma}/(1-\gamma)$. (Expected utility is itself a random variable, because it is a function of current wealth.) To understand how expected utility evolves over time, it is convenient to multiply by $1-\gamma$ —which is negative under our maintained assumption that $\gamma > 1$ —and work with a rescaled variable $X_t = W_t^{1-\gamma}$. By Itô's lemma, this follows the process

$$(12) \quad \frac{dX}{X} = (1-\gamma) \left(r_f + \alpha\hat{\mu} - \theta - \frac{1}{2}\gamma\alpha^2\sigma^2 \right) dt + (1-\gamma)\alpha\sigma dZ + \left[(1-\alpha L)^{1-\gamma} - 1 \right] dN.$$

This is a standard calculation but we provide further detail in the appendix. The drift of dX/X is therefore

$$(13) \quad (1-\gamma) \left(r_f + \alpha\hat{\mu} - \theta - \frac{1}{2}\gamma\alpha^2\sigma^2 \right) + \omega E \left[(1-\alpha L)^{1-\gamma} - 1 \right] = (1-\gamma)(r_{CE} - \theta),$$

where we have used the fact that $E dN = \omega dt$. Sustainability requires that the drift of X is nonpositive: that is, $\theta \leq r_{CE}$. Equation (11) follows.

If the consumption-wealth ratio, θ , is larger than θ_{con} then X has positive drift, and hence expected utility has negative drift: the optimal consumption-investment decision induces declining expected utility over time, on average.

The optimal sustainable consumption-wealth ratio, θ_{sus} , is given by whichever of θ_{con} and θ_{unc} is smaller. If the unconstrained case features a lower consumption-wealth ratio, then it certainly satisfies the constraint and delivers higher utility. If not, the unconstrained case does not satisfy the constraint, so that θ_{con} is the best we can do. Thus

$$(14) \quad \theta_{\text{sus}} = \min \{ \theta_{\text{unc}}, \theta_{\text{con}} \}.$$

Equivalently, θ_{con} is the highest possible sustainable consumption-wealth ratio.

It follows from equations (10) and (11) that

$$(15) \quad \theta_{\text{unc}} = \frac{1}{\gamma}\rho + \left(1 - \frac{1}{\gamma} \right) \theta_{\text{con}}.$$

Equations (14) and (15) have several interesting implications. First, the sustainability constraint binds if and only if $\rho > \theta_{\text{con}} = r_{CE}$ (or, equivalently, if and only if $\rho > \theta_{\text{unc}}$). Related to this, we can show that in the absence of a sustainability constraint,

$$(16) \quad E_0 X_t = X_0 e^{(\rho - \theta_{\text{unc}})t}.$$

The term $\rho - \theta_{\text{unc}}$ in equation (16) equals $(1 - 1/\gamma)(\rho - r_{CE})$. If impatience is sufficiently high that $\rho > \theta_{\text{unc}}$, or equivalently $\rho > r_{CE}$, then $X_t = W_t^{1-\gamma}$

is expected to grow without limit in an unconstrained equilibrium, so expected utility is expected to decline without limit.⁷ The sustainability constraint binds in this circumstance.

Second, equation (15) shows that the moderating influence of ρ makes θ_{unc} less sensitive than θ_{con} to changes in other parameters of the model, holding ρ fixed.

Third, equation (15) implies that the behavior of an extremely risk-averse individual is little affected by the presence or absence of a sustainability constraint, as $\theta_{\text{unc}} \approx \theta_{\text{con}}$ if γ is large. This reflects the fact that highly concave utility leads an agent to choose a flat consumption path that is close to sustainable, regardless of the level of ρ .

Fourth, equations (14) and (15) show that θ_{sus} and θ_{unc} can easily be calculated from knowledge of θ_{con} , so we can focus our analysis on the determinants of θ_{con} .

Finally, we can use this analysis to analyse how and why the social discount rate used in, say, the *Stern Review* (2006), might differ from the quantity ρ that enters an individual's utility function. The *Stern Review* emphasizes the importance of the discount rate in making welfare comparisons across generations separated by long tracts of time, eventually settling on a value of 0.1%. Weitzman's (2007b) review of the *Review* describes this as "a decidedly minority paternalistic view" and worries that "For most economists, a major problem ... is that people are not observed to behave as if they are operating with [the discount rate] $\delta \approx 0$ ".

In our setting, individuals unconstrained by sustainability will use the discount rate $\rho > 0$ in calculations. Might sustainability justify a lower social discount rate suitable for use in a *Stern Review*-like exercise?⁸

To answer this question, define the social discount rate $\hat{\rho}$ via the equation $\theta_{\text{unc}}(\hat{\rho}) = \theta_{\text{sus}}$. With this definition, $\hat{\rho}$ is the hypothetical discount rate that should be used by a social planner who wants to impose sustainability. Equations (14) and (15) imply that

$$(17) \quad \hat{\rho} = \min \{\rho, \theta_{\text{con}}\} = \min \{\rho, r_{CE}\} .$$

If the sustainable consumption-wealth ratio is lower than the unconstrained time discount rate ρ , this represents an alternative justification for using a social discount rate lower than an individual's discount rate, ρ ; nonetheless, it suggests a higher social discount rate than does the Ramsey rule, which sets $\hat{\rho}$ equal to zero. We return to the comparison of the sustainable and Ramsey rules in Section III.

We now turn to the implications of sustainability for the portfolio choice decision. The next result shows that our sustainability constraint does not affect the optimal investment choice, so that its impact is felt purely through the consumption-savings decision, as analyzed above.

Intuitively, it is not optimal to distort portfolio choice because doing so affects expected utility in the same way in all periods. Distorting the portfolio choice

⁷Expected wealth will decline toward zero if ρ is sufficiently large; but if ρ is sufficiently close to θ_{con} then wealth has positive drift despite the negative drift in expected utility.

⁸Weitzman (2007b) points out that model uncertainty provides another justification.

decision away from the unconstrained optimum therefore does not relax the constraint; nor (by definition) does it directly benefit the objective function. By contrast, in papers such as Dybvig (1995) or Campbell and Sigalov (2022) that feature constraints on consumption as opposed to welfare, it may be optimal to distort portfolio choice relative to the unconstrained optimum in order to relax the constraint.

Result 2. *The optimal investment choice is unaffected by the presence of the sustainability constraint. The optimal risky asset allocation, α , continues to satisfy*

$$(18) \quad \hat{\mu} - \alpha\gamma\sigma^2 = \omega E [L(1 - \alpha L)^{-\gamma}],$$

as in the unconstrained case (6).

PROOF:

If the constraint binds, we can use it to eliminate θ from the objective function (4), giving

$$(19) \quad U_{\text{con},0} = \frac{W_0^{1-\gamma} \left(r_f + \alpha\hat{\mu} - \frac{1}{2}\gamma\alpha^2\sigma^2 + \omega \frac{E[(1-\alpha L)^{1-\gamma} - 1]}{1-\gamma} \right)^{1-\gamma}}{1-\gamma} \frac{1}{\rho}.$$

Maximizing equation (19) with respect to α , we find the first-order condition (18).

As a corollary of Results 1 and 2, the sustainable strategy is Pareto-efficient because it is identical to the unconstrained-optimal strategy for some choice of ρ .

A. Bounding the sustainable consumption-wealth ratio

If there are no jumps, as is commonly assumed in the literature, we can use the Merton formula (7) to eliminate α from equation (8), giving

$$(20) \quad \theta_{\text{con}} = r_f + \frac{1}{2} \frac{\mu^2}{\gamma\sigma^2}.$$

Equation (20) can be rewritten, again using condition (7), as

$$(21) \quad \theta_{\text{con}} = \frac{1}{2} \times r_f + \frac{1}{2} \times \underbrace{[(1 - \alpha)r_f + \alpha(r_f + \mu)]}_{\text{expected return on optimally invested wealth}}.$$

This shows that—in the absence of jumps—the certainty-equivalent return and hence the constrained consumption-wealth ratio lie halfway between the riskless return and the expected return on wealth. With plausible parameter values, the maximum sustainable consumption-wealth ratio θ_{con} is therefore considerably higher than the riskless rate. If, say, the riskless rate is $r_f = 2\%$, the expected return on risky capital is $\mu + r_f = 10\%$, its volatility is $\sigma = 20\%$, and risk aversion is 2, then the constrained consumption-wealth ratio is 6%.

More generally, we have the following result.

Result 3. *We have the bounds*

$$(22) \quad r_f + \frac{1}{2}\gamma\alpha^2\sigma^2 \leq \theta_{con} \leq r_f + \alpha\mu - \frac{1}{2}\gamma\alpha^2\sigma^2.$$

In particular, the sustainable consumption-wealth ratio lies between the riskless rate (r_f) and the expected return on wealth ($r_f + \alpha\mu$).

If there are no jumps, the sustainable consumption-wealth ratio is exactly halfway between the riskless rate and the expected return on wealth.

With jumps of deterministic size L , and assuming $\alpha > 0$, the sustainable consumption-wealth ratio is higher than the halfway point if jumps represent bad news, $L > 0$, and lower if jumps represent good news, $L < 0$.

Result 3 shows that the constrained consumption-wealth ratio must lie between the riskless return and the expected return on wealth, with the precise location determined by the arrival rate and distribution of jump sizes. Importantly, the upper and bounds on the sustainable consumption-wealth ratio do not require knowledge of the frequency or size distribution of jumps, though jumps are captured indirectly via their influence on the riskless rate, expected return on risky capital, and the optimal allocation to risky capital, α . In an equilibrium in which risk is inescapable, α must equal one: in this case, only the riskless rate and average return on risky capital must be estimated. These quantities are relatively easy to estimate even in economies with jumps, as Barro (2006) points out.

Result 3 also suggests, as a rule of thumb, that if we think of rare events as representing bad news rather than good news, then the maximum sustainable consumption-wealth ratio should be *higher* than the halfway point between the riskless rate and the expected return on wealth, so that the halfway point itself is sustainable.⁹

B. Sustainable growth

We have seen that sustainability places an upper limit on the rate at which wealth is consumed. Put differently, the sustainability constraint requires that there is enough saving that the expected growth rate of the economy¹⁰ is no less than some lower limit.

Result 4. *Sustainability requires that consumption and wealth have positive drift in levels: that is, $g = E \frac{dC}{C} = E \frac{dW}{W}$ is positive.*

If $\gamma > 1$, sustainability even requires that consumption and wealth have positive drift in logs: that is, $g_{\log} = E d \log C = E d \log W$ is positive.

⁹The proof of Result 3 provides a general condition for arbitrary jump size distributions under which the sustainable consumption-wealth ratio exceeds the halfway point.

¹⁰As measured by the growth rate either of wealth or of consumption. The two are equivalent because the consumption-wealth ratio is constant in our setting.

If equilibrium requires that $\alpha = 1$ —that is, if risk is inescapable—then

$$(23) \quad g = \frac{1}{2}\gamma\sigma^2 + \frac{\omega}{\gamma-1} \mathbb{E} \left[(1-L)^{1-\gamma} - 1 - (\gamma-1)L \right]$$

and

$$(24) \quad g_{\log} = \frac{1}{2}(\gamma-1)\sigma^2 + \frac{\omega}{\gamma-1} \mathbb{E} \left[(1-L)^{1-\gamma} - 1 + (\gamma-1)\log(1-L) \right]$$

when the sustainability constraint binds. Lower growth rates are not sustainable. All four terms on the right-hand sides of equations (23) and (24) are positive if $\gamma > 1$.

The intuition for this result is straightforward. Growth, g , reflects the portion of the return on invested wealth, $r_f + \alpha\mu$, that is not consumed. Thus, when the sustainability constraint binds,

$$(25) \quad g = r_f + \alpha\mu - \theta_{\text{con}} = r_f + \alpha\mu - r_{CE}.$$

This difference is always positive and equals half the risk premium on invested wealth in the case where there are no jumps.

When the sustainability constraint binds, expected utility in the distant future is expected to be the same as expected utility today. But because risk cumulates over time, later generations, who are exposed to more risk, must be compensated with higher average levels of wealth and hence consumption if their expected utility is to be held constant.¹¹

A counterintuitive implication of Result 4 is that as one looks into the far-distant future expected utility is overwhelmingly likely to be higher than its current value: in an economy that grows on average, expected utility at time t approaches its upper bound (of zero) almost surely as t approaches infinity. Nonetheless, expected utility is constant over time *in expectation* because (echoing the result of Martin, 2012) there is a sting in the tail: there are a vanishingly small number of extreme paths in which expected utility in the future is arbitrarily low.

C. Numerical examples

Table 1 presents some numerical examples to illustrate the properties we have discussed.

The first line of the table considers a case with no jumps. The riskless return and risk premium are each equal to 4.5%, so that the risky asset's expected

¹¹Result 4 illustrates the distinction between our sustainability constraint and the arithmetic and geometric constraints considered by Campbell and Sigalov (2022), which impose zero drift in wealth or in log wealth, respectively. Moreover, the Campbell and Sigalov constraints generally distort portfolio choice, whereas our sustainability constraint does not.

TABLE 1—NUMERICAL EXAMPLES

	r_f	μ	σ	ω	L	α	θ_{con}	g	$g_{\log}$	halfway
No disasters	0.045	0.045	0.15	0	0	1	0.0675	0.0225	0.0113	0.0675
Avoidable disasters	0.045	0.045	0.15	0.02	0.5	0.698	0.0617	0.0147	0.0076	0.0607
Unavoidable disasters	0.015	0.075	0.15	0.02	0.5	1	0.0575	0.0325	0.0174	0.0525

return is 9%, and the risky asset's volatility is 15%. With risk aversion $\gamma = 2$ (as is assumed throughout the table) Result 2 implies that it is optimal to put all wealth into the risky asset, $\alpha = 1$. The maximum sustainable consumption-wealth ratio is $\theta_{\text{con}} = 6.75\%$, by Result 1: this is exactly halfway between the riskless return and the expected return on wealth, as shown in equation (21) and reported in the final column of the table. The minimum expected growth rate that is consistent with sustainability is 2.25%, by Result 4. These numbers add up to the expected return on wealth, 9%, as required by equation (25).

The second line of Table 1 holds the riskless return and risk premium constant, but adds disasters that destroy 50% of wealth on arrival, and which arrive at rate 2% per year. These make the risky asset less attractive, so the optimal response is to reduce risk exposure, setting $\alpha = 0.698$. The maximum sustainable consumption-wealth ratio declines to 6.17%, and this is associated with the minimum sustainable growth rate $g = 1.47\%$. Again, the sustainable consumption wealth ratio and growth rate add up to the expected return on wealth, $\theta_{\text{con}} + g = r_f + \alpha\mu$.

In the economy described in the second line, the scale of two technologies—one risky, the other riskless—can be adjusted arbitrarily. But we might imagine an equilibrium in which society cannot eliminate risk no matter how much it might wish to do so. If we impose this requirement, holding the total return on the risky technology constant at 9%, as in the first two lines, then the riskless rate must adjust endogenously so that society is content to bear the inescapable risk of its invested wealth—that is, so that $\alpha = 1$.

The third line of Table 1 considers this case. The interest rate declines to 1.5%, so that the risk premium on the risky asset is 7.5%. At these levels, it is indeed optimal to invest fully in the risky technology. The maximum sustainable consumption-wealth ratio of 5.75% lies slightly above the halfway point between the riskless return and the expected return on the risky technology, consistent with Result 3.

Figure 1 expands on this last calibration to show how the sustainable consumption-wealth ratio varies with the severity of jumps. As in the third line of Table 1, we set risk aversion $\gamma = 2$ and assume an expected return on risky capital of 9%, Brownian volatility $\sigma = 15\%$, a jump probability $\omega = 2\%$, and jumps of deterministic size L . The horizontal axis shows different values for L , where positive values correspond to negative jumps (losses) in wealth, and negative values correspond to positive jumps in wealth. In the left panel, the constrained consumption-wealth

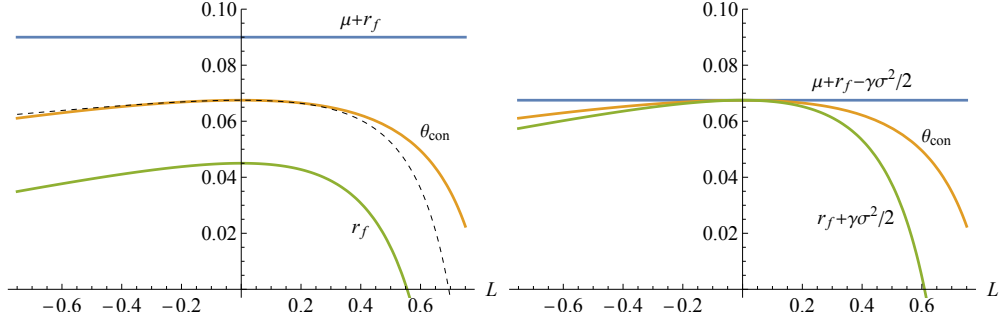


FIGURE 1. θ_{con} AND THE UPPER AND LOWER BOUNDS FOR VARIOUS DETERMINISTIC JUMP SIZES L , WITH $\gamma = 2$, $\sigma = 0.15$, $\omega = 0.02$, $\mu + r_f = 0.09$. JUMPS ARE BAD NEWS IF L IS POSITIVE AND GOOD NEWS IF L IS NEGATIVE. THE DASHED LINE IN THE LEFT PANEL INDICATES THE MIDPOINT OF THE RISKLESS RATE AND EXPECTED RETURN ON THE RISKY TECHNOLOGY.

ratio θ_{con} is plotted along with the expected risky asset return $r_f + \mu$ (constant at 9%) and the endogenously determined riskfree interest rate r_f . The maximum sustainable consumption-wealth ratio is halfway between the two returns in the Brownian case; it is closer to the risky asset return in the bad-jump region where $L > 0$, and closer to the riskfree interest rate in the good-jump region where $L < 0$. In the right panel, the maximum sustainable consumption-wealth ratio is plotted along with the upper and lower bounds from Result 3. The bounds are tight in the Brownian case ($L = 0$), and widen out as the absolute jump size increases.

III. Sustainability and the Ramsey Rule

We have interpreted sustainability as requiring that expected utility should not be allowed to decline over time. One can imagine representatives of each generation attempting to agree (at time 0, behind the veil of ignorance) on a savings policy that gives each generation the same expected utility. Put another way, these representatives maximize the expected utility of the worst-off generation, following the “difference principle” of Rawls (1999). Equation (4) shows that this is equivalent to ensuring that $E_0 W_t^{1-\gamma}/(1-\gamma)$ (or equivalently, as the consumption-wealth ratio is constant, $E_0 C_t^{1-\gamma}/(1-\gamma)$) is constant across t .

As an alternative rule, one might also imagine considering the possibility that the representatives aim to maximize *average* utility across generations. This is equivalent to maximizing

$$(26) \quad \int_{t=0}^{\infty} E_0 \frac{C_t^{1-\gamma}}{1-\gamma} dt = E_0 \int_{t=0}^{\infty} \frac{C_t^{1-\gamma}}{1-\gamma} dt.$$

This is the problem faced by an unconstrained agent with pure time preference rate $\rho = 0$. It leads to the savings rule proposed by Ramsey (1928), who argued on ethical grounds that the rate of pure time preference should be zero. Setting $\rho = 0$ in equation (10), we arrive at the Ramsey consumption-wealth ratio

$$(27) \quad \theta_{\text{Ramsey}} = \left(1 - \frac{1}{\gamma}\right) r_{\text{CE}}.$$

The next result follows by comparing (27) with (11).

Result 5. *There is a simple relationship between the sustainable consumption-wealth ratio and the Ramsey consumption-wealth ratio:*

$$(28) \quad \theta_{\text{Ramsey}} = \left(1 - \frac{1}{\gamma}\right) \theta_{\text{con}}.$$

The two rules are similar at high levels of risk aversion, but the Ramsey rule is substantially more conservative at plausible values of γ . The Ramsey rule dictates 10% less consumption than our sustainable rule if $\gamma = 10$; 25% less consumption if $\gamma = 4$; and 50% less consumption if $\gamma = 2$. In the log utility case $\gamma = 1$, the Ramsey rule cannot be implemented at all, as it sets the consumption-wealth ratio equal to the Ramsey rate of time preference—that is, to zero.

IV. Conclusion

We have argued, in the spirit of Koopmans (1960, 1967), that the implication of an ethical criterion—sustainability—for social discounting and consumption decisions depends on the production technology available to society. Specifically, in a risky world with a binding sustainability constraint, the sustainable social rate of time preference and consumption-wealth ratio, which equal one another, are not equal to either the riskless interest rate or the risky return on invested wealth, but lie in between these two. In the special case where invested wealth has only Brownian risk and no jump risk, the sustainable social rate of time preference is the equal-weighted average of the riskless interest rate and the risky return.

We have made this point in the context of a model in which the parameters governing the distribution of returns are known. We have therefore ignored parameter uncertainty, a phenomenon emphasized by Weitzman (2007a, 2007b, 2009). We have also ignored the possibility that returns may not be i.i.d., because expected returns or risks change over time. Models with non-i.i.d. returns in general imply time-varying consumption growth and a term structure of discount rates. When consumption growth is persistent, this term structure is generally downward-sloping for safe investments and upward-sloping for risky ones as in the long-run risk model of Bansal and Yaron (2004). Gollier (2002) emphasizes the potential importance of a downward-sloping term structure of discount rates for social dis-

counting. Our i.i.d. model has discount rates that are invariant to the horizon of an investment.

Although we have emphasized the sustainable social rate of time preference, we conclude by noting that this is not the same as the appropriate social discount rate that should be applied to an investment project. That discount rate depends on the project's risk. For a riskless project, the appropriate discount rate is the riskless interest rate, which is lower than the sustainable social rate of time preference in a risky world; and for a project that has the same risk as society's invested wealth, the appropriate discount rate is the expected risky return, which is higher than the sustainable social rate of time preference. Some previous discussions of social discounting have obscured these distinctions by ignoring the risk that society faces. Our analysis is deliberately simple in order to achieve clarity about these issues.

References

- Arrow, Kenneth, Partha Dasgupta, Lawrence Goulder, Gretchen Daily, Paul Ehrlich, Geoffrey Heal, Simon Levin, Karl-Göran Mäler, Stephen Schneider, David Starrett, and Brian Walker, 2004, "Are We Consuming Too Much?", *Journal of Economic Perspectives* 18, 147–172.
- Asheim, Geir B., 2007, *Justifying, Characterizing and Indicating Sustainability*, Springer, Dordrecht, The Netherlands.
- Backus, David K., Mikhail B. Chernov, and Ian W. R. Martin, 2011, "Disasters Implied by Equity Index Options", *Journal of Finance* 66, 1969–2012.
- Bansal, Ravi, and Amir Yaron, 2004, "Risks for the Long Run: A Potential Resolution of Asset Pricing Puzzles", *Journal of Finance* 59, 1481–1509.
- Barro, Robert J., 2006, "Rare Disasters and Asset Markets in the Twentieth Century", *Quarterly Journal of Economics* 121, 823–866.
- Barro, Robert J., 2023, "r Minus g", *Review of Economic Dynamics* 48, 1–17.
- Blanchard, Olivier J., 1985, "Debt, Deficits, and Finite Horizons", *Journal of Political Economy* 93, 223–247.
- Campbell, John Y. and Roman Sigalov, 2022, "Portfolio Choice with Sustainable Spending: A Model of Reaching for Yield", *Journal of Financial Economics* 143, 188–206.
- Cline, William R., 1992, *The Economics of Global Warming*, Institute for International Economics, Washington, DC.
- Cont, Rama, and Peter Tankov, 2004, *Financial Modelling with Jump Processes*, Chapman & Hall/CRC, Boca Raton, FL.

- Dasgupta, Partha, 2001, *Human Well-Being and the Natural Environment*, Oxford University Press, Oxford, UK.
- Dasgupta, Partha, 2008, “Discounting Climate Change”, *Journal of Risk and Uncertainty* 37, 141–169.
- Dasgupta, Partha, 2021, *The Economics of Biodiversity: The Dasgupta Review*, HM Treasury, London, UK.
- Dasgupta, Partha, and Geoffrey Heal, 1974, “The Optimal Depletion of Exhaustible Resources”, *Review of Economic Studies* 41, 3–28.
- Dybvig, Philip H., 1995, “Duesenberry’s Ratcheting of Consumption: Optimal Dynamic Consumption and Investment Given Intolerance for any Decline in Standard of Living”, *Review of Economic Studies* 62, 287–313.
- Gollier, Christian, 2002, “Discounting an Uncertain Future”, *Journal of Public Economics* 85, 149–166.
- Gollier, Christian, 2021, “The Welfare Cost of Ignoring the Beta”, unpublished paper, Toulouse School of Economics.
- Harsanyi, John C., 1955, “Cardinal Welfare, Individualistic Ethics, and Interpersonal Comparisons of Utility”, *Journal of Political Economy* 63, 309–321.
- Hartwick, John M., 1977, “Intergenerational Equity and the Investing of Rents from Exhaustible Resources”, *American Economic Review* 67, 972–974.
- Howarth, Richard B., 1995, “Sustainability Under Uncertainty: A Deontological Approach,” *Land Economics* 71, 417–427.
- Koopmans, Tjalling, 1960, “Stationary Ordinal Utility and Impatience”, *Econometrica* 28, 287–309.
- Koopmans, Tjalling, 1967, “Objectives, Constraints, and Outcomes in Optimal Growth Models”, *Econometrica* 35, 1–15.
- Llavorador, Humberto, John E. Roemer, and Joaquim Silvestre, 2015, *Sustainability for a Warming Planet*, Harvard University Press, Cambridge, MA.
- Martin, Ian W. R., 2012, “On the Valuation of Long-Dated Assets”, *Journal of Political Economy* 120, 346–358.
- Martin, Ian W. R., 2013, “Consumption-Based Asset Pricing with Higher Cumulants”, *Review of Economic Studies* 80, 745–773.
- Merton, Robert C., 1969, “Lifetime Portfolio Selection Under Uncertainty: The Continuous-Time Case”, *Review of Economics and Statistics* 51, 247–257.

- Merton, Robert C., 1971, "Optimum Consumption and Portfolio Rules in a Continuous-Time Model", *Journal of Economic Theory* 3, 373–413.
- Nordhaus, William D., 1994, *Managing the Global Commons: The Economics of Climate Change*, MIT Press, Cambridge, MA.
- Parfit, Derek, 1984, *Reasons and Persons*, Oxford University Press, Oxford, UK.
- Pezzey, John, 1992, "Sustainability: An Interdisciplinary Guide," *Environmental Values* 1, 321–362.
- Ramsey, Frank P., 1928, "A Mathematical Theory of Saving", *Economic Journal* 38, 543–559.
- Rawls, John, 1999, *A Theory of Justice*, Revised edition, Oxford University Press, Oxford, UK.
- Rietz, Thomas A., 1988, "The Equity Premium: A Solution", *Journal of Monetary Economics* 22, 117–131.
- Romer, Paul M., 1986, "Increasing Returns and Long-Run Growth", *Journal of Political Economy* 94, 1002–1037.
- Solow, Robert M., 1974, "Intergenerational Equity and Exhaustible Resources", *Review of Economic Studies* 41, 29–46.
- Solow, Robert M., 1993, "An Almost Practical Step Toward Sustainability," *Resources Policy*, 19, 162–172
- Stern, Nicholas H., 2006, *Stern Review: The Economics of Climate Change*, Cambridge University Press, Cambridge, UK.
- Stern, Nicholas H., 2016, *Why Are We Waiting? The Logic, Urgency, and Promise of Tackling Climate Change*, MIT Press, Cambridge, MA.
- Weitzman, Martin L., 2007a, "Subjective Expectations and Asset-Return Puzzles", *American Economic Review* 97, 1102–1130.
- Weitzman, Martin L., 2007b, "A Review of *The Stern Review on the Economics of Climate Change*," *Journal of Economic Literature* 45, 703–724.
- Weitzman, Martin L., 2009, "On Modeling and Interpreting the Economics of Catastrophic Climate Change", *Review of Economics and Statistics* 91, 1–19.
- World Commission on Environment and Development, 1987, *Our Common Future*, Oxford University Press, New York, NY.
- Zeckhauser, Richard J., and W. Kip Viscusi, 2008, "Discounting Dilemmas: Editors' Introduction", *Journal of Risk and Uncertainty* 37, 95–106.

APPENDIX

Details regarding the derivation of equation (3). It follows by applying Itô's formula for semimartingales to (2) that

$$(A1) \quad d \log C = \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \alpha^2 \sigma^2 - \theta \right) dt + \alpha \sigma dZ + \log(1 - \alpha L) dN.$$

See, for example, Proposition 8.19 of Cont and Tankov (2004). Heuristically, we can derive (A1) by writing

$$d \log C = \frac{1}{C} dC - \frac{1}{2!} \frac{1}{C^2} (dC)^2 + \frac{1}{3!} \frac{2}{C^3} (dC)^3 - \frac{1}{4!} \frac{6}{C^4} (dC)^4 + \dots$$

and using the relationships $dt dN = dZ dN = 0$ and $dN^k = dN$ for all $k > 0$, in addition to the standard properties of dZ and the fact that $\log(1 + x) = x - x^2/2 + x^3/3 - x^4/4 + \dots$ if $|x| < 1$, which holds when $x = -\alpha L$ because the agent will never risk bankruptcy.

Integrating forwards, exponentiating, using $C_0 = \theta W_0$, and raising to the power $1 - \gamma$, we have

$$(A2) \quad C_t^{1-\gamma} = W_0^{1-\gamma} \theta^{1-\gamma} \exp \left\{ (1-\gamma) \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \alpha^2 \sigma^2 - \theta \right) t + \alpha(1-\gamma) \sigma Z_t \right\} \prod_{i=1}^{N_t} (1 - \alpha L_i)^{1-\gamma}.$$

Writing L for a representative of the i.i.d. L_i , we have

$$(A3) \quad E C_t^{1-\gamma} = W_0^{1-\gamma} \theta^{1-\gamma} \exp \left\{ (1-\gamma) \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \gamma \alpha^2 \sigma^2 - \theta \right) t + \omega E \left[(1 - \alpha L)^{1-\gamma} - 1 \right] t \right\}.$$

This holds because N_t , Z_t , and L_i are independent, and using (i) the law of iterated expectations, (ii) the fact that N_t is a Poisson random variable with parameter ωt , (iii) the i.i.d. nature of the L_i , and (iv) the series definition of the exponential function to calculate

$$\begin{aligned} E \prod_{i=1}^{N_t} (1 - \alpha L_i)^{1-\gamma} &\stackrel{(i)}{=} E \left[E \left(\prod_{i=1}^{N_t} (1 - \alpha L_i)^{1-\gamma} \mid N_t \right) \right] \\ &\stackrel{(ii)}{=} \sum_{n=0}^{\infty} e^{-\omega t} \frac{(\omega t)^n}{n!} E \prod_{i=1}^n (1 - \alpha L_i)^{1-\gamma} \\ &\stackrel{(iii)}{=} \sum_{n=0}^{\infty} e^{-\omega t} \frac{(\omega t)^n}{n!} \left(E \left[(1 - \alpha L)^{1-\gamma} \right] \right)^n \\ &\stackrel{(iv)}{=} \exp \left\{ \omega E \left[(1 - \alpha L)^{1-\gamma} - 1 \right] t \right\}. \end{aligned}$$

Details regarding the derivation of equation (12). As above, equation (12) follows directly from Itô's lemma, but we can understand the evolution of the rescaled variable $X = W^{1-\gamma}$ heuristically by writing

$$dX = (1-\gamma)W^{-\gamma} dW + \frac{\gamma(\gamma-1)}{2}W^{-\gamma-1} dW^2 - \frac{\gamma(\gamma-1)(\gamma+1)}{6}W^{-\gamma-2} dW^3 + \dots$$

Rearranging, we have

$$\begin{aligned} \frac{dX}{X} &= (1-\gamma)\frac{dW}{W} + \frac{\gamma(\gamma-1)}{2}\left(\frac{dW}{W}\right)^2 - \frac{\gamma(\gamma-1)(\gamma+1)}{6}\left(\frac{dW}{W}\right)^3 + \dots \\ &= (1-\gamma)\left(r_f + \alpha\hat{\mu} - \theta - \frac{1}{2}\gamma\alpha^2\sigma^2\right)dt + (1-\gamma)\alpha\sigma dZ + \\ &\quad + \left[(\gamma-1)\alpha L + \frac{\gamma(\gamma-1)}{2}\alpha^2 L^2 + \frac{\gamma(\gamma-1)(\gamma+1)}{6}\alpha^3 L^3 + \dots\right]dN \\ &= (1-\gamma)\left(r_f + \alpha\hat{\mu} - \theta - \frac{1}{2}\gamma\alpha^2\sigma^2\right)dt + (1-\gamma)\alpha\sigma dZ + \left[(1-\alpha L)^{1-\gamma} - 1\right]dN, \end{aligned}$$

as required, where we use the binomial expansion of $(1-\alpha L)^{1-\gamma}$ in the last line.

PROOF OF RESULT 3:

Define $\mathbf{m}(x) = \mathbb{E}[(1-\alpha L)^{-x}]$. This is the moment-generating function of the random variable $J = -\log(1-\alpha L)$, so $\mathbf{m}(x)$ is a convex function of x (indeed, the cumulant-generating function $\log \mathbf{m}(x)$ is convex). By Result 1 we can write the maximum sustainable consumption-wealth ratio either as

$$\theta_{\text{con}} = r_f + \frac{1}{2}\gamma\alpha^2\sigma^2 + \omega \left[\mathbf{m}(\gamma) - \mathbf{m}(\gamma-1) - \frac{\mathbf{m}(\gamma-1) - \mathbf{m}(0)}{\gamma-1} \right]$$

or as

$$\theta_{\text{con}} = r_f + \alpha\mu - \frac{1}{2}\gamma\alpha^2\sigma^2 - \omega \left[\frac{\mathbf{m}(\gamma-1) - \mathbf{m}(0)}{\gamma-1} - (\mathbf{m}(0) - \mathbf{m}(-1)) \right].$$

The upper and lower bounds follow by noting that the expressions in the square brackets are (collectively) positive in each equation, by virtue of the convexity of $\mathbf{m}(x)$.

Adding the two together and dividing by two, it follows that

$$\theta_{\text{con}} = \frac{r_f + r_f + \alpha\mu}{2} + \frac{\omega}{2} \left[\mathbf{m}(\gamma) - \mathbf{m}(\gamma-1) - 2\frac{\mathbf{m}(\gamma-1) - \mathbf{m}(0)}{\gamma-1} + (\mathbf{m}(0) - \mathbf{m}(-1)) \right].$$

The condition for $\theta_{\text{con}} \geq \frac{r_f + r_f + \alpha\mu}{2}$ is therefore that

$$(A4) \quad \mathbf{m}(\gamma) - \mathbf{m}(\gamma-1) - 2\frac{\mathbf{m}(\gamma-1) - \mathbf{m}(0)}{\gamma-1} + \mathbf{m}(0) - \mathbf{m}(-1) \geq 0.$$

This may or may not hold for different size distributions L . Suppose, however, that L is deterministic and $L \geq 0$. Then $\mathbf{m}(x) = e^{Jx}$ where $J = -\log(1-\alpha L) \geq 0$. In this case, condition (A4) becomes

$$e^{J\gamma} - e^{J(\gamma-1)} - 2 \frac{e^{J(\gamma-1)} - 1}{\gamma - 1} + 1 - e^{-J} \geq 0.$$

We fix $\gamma > 1$ and view the left-hand side of this inequality as a function of J . Defining

$$h(J) = e^{J\gamma} - e^{J(\gamma-1)} - 2 \frac{e^{J(\gamma-1)} - 1}{\gamma - 1} + 1 - e^{-J},$$

we must show that $h(J) \geq 0$ for arbitrary $J \geq 0$. As $h(0) = 0$, it is enough to show that $h'(J) \geq 0$ for $J \geq 0$. By direct calculation, $h'(J) = \gamma e^{J\gamma} - (\gamma+1)e^{J(\gamma-1)} + e^{-J}$. As $h'(0) = 0$, it remains to show that $h''(J) \geq 0$ for $J \geq 0$, as this will establish that $h'(J) \geq 0$ for arbitrary $J \geq 0$, and hence that $h(J) \geq 0$ for arbitrary $J \geq 0$. But this holds:

$$h''(J) = \gamma^2 (e^{J\gamma} - e^{J(\gamma-1)}) + e^{-J} (e^{J\gamma} - 1) \geq 0.$$

If $L \leq 0$ and hence $J \leq 0$, the same logic applies but the inequality is reversed.

PROOF OF RESULT 4:

As

$$(A5) \quad \frac{dW}{W} = \left\{ \frac{1}{2} \gamma \alpha^2 \sigma^2 + \frac{\omega}{\gamma - 1} \mathbb{E} \left[(1 - \alpha L)^{1-\gamma} - 1 \right] \right\} dt + \alpha \sigma dZ - \alpha L dN,$$

the drift of wealth is

$$(A6) \quad \mathbb{E} \frac{dW}{W} = \left(\frac{1}{2} \gamma \alpha^2 \sigma^2 + \frac{\omega}{\gamma - 1} \mathbb{E} \left[(1 - \alpha L)^{1-\gamma} - 1 + \alpha L(1 - \gamma) \right] \right) dt,$$

and both terms in the brackets are positive. (To see that the second term is positive, note that Bernoulli's inequality states that $(1+x)^r \geq 1+rx$ if $1+x$ is positive and $r \leq 0$ or $r \geq 1$. Under our maintained assumption that $\gamma > 1$, it follows that $(1 - \alpha L)^{1-\gamma} \geq 1 + (\gamma - 1)\alpha L$.)

Similarly,

$$(A7) \quad \mathbb{E} d \log W = \left(\frac{1}{2} (\gamma - 1) \alpha^2 \sigma^2 + \frac{\omega}{\gamma - 1} \mathbb{E} \left[(1 - \alpha L)^{1-\gamma} - 1 - (1 - \gamma) \log(1 - \alpha L) \right] \right) dt.$$

Again both terms in the brackets are positive. This is obvious for the first term; for the second, write

$$\mathbb{E} \left[(1 - \alpha L)^{1-\gamma} - 1 - (1 - \gamma) \log(1 - \alpha L) \right] = \mathbb{E} \left[e^{(\gamma-1)J} - 1 - (\gamma-1)J \right],$$

where $J = -\log(1 - \alpha L)$, and use the fact that $e^y \geq 1 + y$ for all $y \in \mathbb{R}$.

Sustainability with population growth. The analysis in the body of the paper imposes sustainability on a social welfare function defined over aggregate consumption. This is equivalent to sustainability of individual utility only if the population is constant. We now show how to modify our analysis to make individual utility sustainable given constant exogenous population growth at rate g .

If there is population growth, then wealth at time t is shared between more people. Normalizing the initial population size to 1, the wealth of an average individual at time t is $W_t e^{-gt}$, where $g > 0$ is the population growth rate. To ensure that such an average individual's expected utility is nondecreasing, we require¹² that $\tilde{X}_t$ has nonpositive drift, where $\tilde{X}_t = e^{g(\gamma-1)t} X_t$.

As $d\tilde{X}/\tilde{X} = g(\gamma - 1) dt + dX/X$, the sustainability constraint (11) becomes

$$(A8) \quad \theta \leq r_{CE} - g.$$

The right-hand side of (A8) subtracts the population growth rate g from the previous formula for the sustainable consumption-wealth ratio. Sustainability of individual utility is a more demanding requirement in the presence of population growth. However, for realistic population growth rates the central message of the paper remains unchanged: in the presence of risk, the sustainable consumption-wealth ratio exceeds the riskless interest rate r_f and substantially exceeds $r_f - g$, which would be its value in the riskless economy considered by Arrow et al. (2004).

The case of multiple assets. Our results generalize without modification if there are multiple assets whose returns are i.i.d. over time (but potentially correlated across assets), as for any portfolio of asset holdings consumption growth will continue to satisfy equation (2) for appropriate μ , σ , ω , and L .

The log utility case. With log utility, the investor's objective function is

$$U = E \int_0^\infty e^{-\rho t} \log C_t dt, \quad \text{where } \rho > 0.$$

It follows from equation (A1) that

$$\log C_t = \log C_0 + \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \alpha^2 \sigma^2 - \theta \right) t + \alpha \sigma Z_t + \sum_{i=1}^{N_t} \log(1 - \alpha L_i),$$

¹²This condition also ensures nondecreasing expected utility for any class of individuals who have a constant share of the wealth of society. For example, a Blanchard (1985) model with population growth implies that a newborn person has lower wealth than the average currently living person, because more people are born than die at each instant; however, with a constant population growth rate the wealth share of newborn individuals is constant over time. Thus, the constraint that $\tilde{X}_t$ has nonpositive drift ensures that the expected utility of newborn individuals does not decline over time.

and hence

$$\mathbb{E} \log C_t = \log C_0 + \left(r_f + \alpha \hat{\mu} - \frac{1}{2} \alpha^2 \sigma^2 - \theta \right) t + \omega \mathbb{E} [\log (1 - \alpha L)] t.$$

Thus the objective function can be evaluated explicitly as

$$U = \frac{\log W_0 + \log \theta}{\rho} + \frac{r_f + \alpha \hat{\mu} - \frac{1}{2} \alpha^2 \sigma^2 - \theta + \omega \mathbb{E} [\log (1 - \alpha L)]}{\rho^2}.$$

Maximizing with respect to θ and α we find the first-order conditions for an unconstrained optimum,

$$\theta = \rho \quad \text{and} \quad \hat{\mu} - \alpha \sigma^2 = \omega \mathbb{E} [L (1 - \alpha L)^{-1}].$$

The objective function at time t is affine in $\log W_t$, so the sustainability condition requires that $d \log W_t$, or equivalently $d \log C_t$, is driftless, i.e. that

$$\theta \leq r_f + \alpha \hat{\mu} - \frac{1}{2} \alpha^2 \sigma^2 + \omega \mathbb{E} [\log (1 - \alpha L)].$$

We define the constrained solution as before, giving

$$\theta_{\text{con}} = r_f + \alpha \hat{\mu} - \frac{1}{2} \alpha^2 \sigma^2 + \omega \mathbb{E} [\log (1 - \alpha L)].$$

When the constraint binds, we have

$$U = \frac{\log W_0 + \log \theta}{\rho},$$

so α is chosen to maximize the constrained consumption-wealth ratio. We end up with the same first-order condition as in the unconstrained case. Thus the optimal investment choice is the same in the constrained and unconstrained cases, as before. Equations (14) and (15) also hold as before.