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# **r minus g**

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## **r Minus g\***

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### **Abstract**

Long-term data show that the dynamic efficiency condition  $r > g$  holds when  $g$  is represented by the average growth rate of real GDP if  $r$  is the average real rate of return on equity,  $E(r^e)$ , but not if  $r$  is the risk-free rate,  $r^f$ . This pattern accords with a simple disaster-risk model calibrated to fit observed equity premia. If Ponzi (chain-letter) finance by private agents and the government are precluded, the equilibrium can feature  $r^f \leq E(g)$ , a result that does not signal dynamic inefficiency. In contrast,  $E(r^e) > E(g)$  is required for dynamic efficiency, implied by the model, and consistent with the data. The model satisfies Ricardian Equivalence because, without Ponzi finance by the government, a rise in safe assets from increased public debt is matched by an increase in the safe (that is, certain) present value of liabilities associated with net taxes.

\*I have benefited from suggestions by Marios Angeletos, John Campbell, Xavier Gabaix, and Jon Steinsson.

The familiar dynamic efficiency condition is  $r > g$ , where  $r$  is a real rate of return and  $g$  is a rate of economic growth, for example, of real GDP. This condition applies to the steady state of the infinite-horizon neoclassical growth model, as developed in Cass (1965) and Koopmans (1965) and elaborated in Barro and Sala-i-Martin (2004, Ch. 2). The condition rules out excessive saving and investment; specifically, capital is not accumulated in the long run beyond the golden-rule level described in Phelps (1961). In contrast,  $r < g$  is possible in the steady state of the overlapping-generations model developed by Diamond (1965), so that reduced saving and investment can be Pareto improving. In this OLG environment, expansions of public debt and enlargement of pay-as-you-go social security systems may be welfare enhancing. The condition  $r > g$  was highlighted in Abel, et al. (1989), and it arises in many analyses of wealth accumulation and public debt, such as the recent studies by Piketty (2011) and Blanchard (2019).

Whether  $r > g$  applies empirically depends mainly on how one defines  $r$ . The bottom line from the available data since 1870 for 14 OECD countries, shown in Table 1, is that the condition holds if  $r$  is gauged by the average of the realized real rate of return on equity and does not hold if  $r$  equals the average of the realized real rate of return on short-term government bills.<sup>1</sup> The latter variable likely approximates the average of safe real interest rates. Since the  $r > g$  condition holds when  $r$  is based on risky returns (on equity) but not when  $r$  is based on safe returns (approximated by government bills), a key underlying element is the large gap between the expected real rate of return on equity and the safe real interest rate; that is, the equity

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<sup>1</sup>This perspective is consistent with the discussion in Abel, et al. (1989, p.2), who considered estimates of the marginal product of capital but did not look at rates of return on equity. The results accord with the returns data presented in Barro and Ursúa (2008, Table 5), which appear in updated form in Table 1. The underlying numbers come mostly from *Global Financial Data*. Longer-term patterns are studied in Homer and Sylla (1996) and Schmelzing (2020).

premium. This substantial premium provides a lot of space in which  $g$  can fit, so that  $g$  can be simultaneously below the risky rate and above the safe rate.

The  $r$ - $g$  condition depends also on the definition of  $g$ , which is typically based on the long-run growth rate of real GDP. In the usual version of the neoclassical growth model, the relevant transversality condition involves the growth rate of the level of real macroeconomic aggregates, not quantities per capita. This result emerges from a specification in which individuals currently alive are connected as parents to members of future generations; for example, through altruistic linkages. In this case, current households consider the asymptotic present value of all future real income, whether growing per capita or because of population growth.

To be more specific on the long-term empirical patterns, Table 1 shows the means since 1870 (or a more recent year when earlier data are missing) of real rates of return and growth rates for 14 OECD countries with available data. The returns refer to averages of realized arithmetic real rates of return on stocks (based on broad indices such as the S&P 500), short-term bills (analogous to Treasury Bills), and government bonds (around 10-year maturity). The growth rates refer to real GDP per capita, real personal consumer expenditure per capita, and population (which enables calculations of growth rates of levels of real GDP and consumer expenditure). When averaging over the 14 countries, the average annual real rates of return were 7.0% on stocks, 1.1% on bills, and 2.6% on bonds. Averages for annual growth rates were 1.9% for per capita GDP, 1.7% for per capita consumer expenditure, and 0.9% for population. Hence, for levels, the average annual growth rates were 2.8% for GDP and 2.6% for consumer expenditure.<sup>2</sup>

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<sup>2</sup>Results are similar if samples start in 1960, rather than 1870. In the 1960 case, the averages over the 14 countries were 7.8% for stock returns, 1.4% for bill returns, 3.5% for bond returns, 2.1% for per capita GDP, 2.0% for per capita consumer expenditure, and 0.7% for population.

These numbers show that, over the long term, the growth rates of GDP and consumer expenditure were clearly below the real rate of return on equity and above that on bills. In contrast, real rates of return on bonds were close to the growth rates of GDP and consumer expenditure.

To understand what measure of  $r-g$  matters, one needs a theoretical model that can explain a large equity premium. The standard neoclassical growth model is unsatisfactory for this purpose because, in its deterministic setting, there is a single real rate of return and no equity premium. A satisfactory framework requires uncertainty that is sufficient to generate a large equity premium; that is, to resolve the equity-premium puzzle of Mehra and Prescott (1985). I use a simple representative-agent model with disaster risk, following Barro (2009), which built on Rietz (1988) and Barro (2006). The analysis could also be pursued in alternative frameworks that can generate a large equity premium. Prominent possibilities here are the long-run risks framework of Bansal and Yaron (2004)<sup>3</sup> and the heterogeneous-consumers model of Constantinides and Duffie (1996).

## **I. Fruit-tree Model with Stochastic Depreciation**

I use the simplest representative-agent model I have thought of that has sufficient aggregate uncertainty to generate a realistic equity premium and that also determines endogenously the rate of economic growth and the investment/saving decision. The model is an “AK” version of the Lucas fruit-tree model:

$$(1) \quad Y_t = AK_t,$$

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<sup>3</sup>This model features variations in the mean and volatility of long-run growth rates. Other models, such as Gabaix (2012), allow for volatility of disaster risk.

where  $Y_t$  is output (of fruit or seeds) and  $K_t$  is the capital stock in the form of trees. The model is constructed in discrete time but the length of the period is allowed to approach zero. The timing is specified so that  $K_t$  represents the capital stock available at the start of period  $t$  and  $Y_t$  the output produced during period  $t$ . The productivity level,  $A > 0$ , is assumed constant but productivity shocks can be introduced. These shocks would be analogous to the stochastic depreciation introduced below. A simplifying assumption is that the marginal product of capital (equal to the average product) does not diminish as capital is accumulated. This absence of diminishing returns seems most plausible when capital stock and capital services are interpreted broadly to encompass human capital, household durables, intangible capital, etc.

During period  $t$ , output can be consumed as fruit,  $C_t$ , or invested as seed,  $I_t$ , so that

$$(2) \quad C_t = Y_t - I_t = AK_t - I_t.$$

The creation of new trees through planting seeds (that is, gross investment) is assumed to be rapid enough so that, as in the conventional one-sector production framework, the fruit price of a unit of capital is pegged at a price normalized to one.<sup>4</sup> Therefore, in the simplest setting, the price,  $P_t$ , of equity—in the sense of a claim on all of the trees—always equals  $K_t$ . This result corresponds to “Tobin’s  $q$ ” equaling one. In terms of changes over time, the equity price ratio,  $P_{t+1}/P_t$ , would equal the capital-stock ratio,  $K_{t+1}/K_t$ , which equals the output ratio,  $Y_{t+1}/Y_t$ . Therefore, the volatilities of equity prices and output would be the same. In contrast, empirically observed equity prices are far more volatile than output, gauged by real GDP.

In practice, there are many reasons that equity valuations for businesses would depart from the reproduction cost of the underlying capital stock. As an example, the price of goods sold might be a variable markup,  $1 + \mu_t$ , of the underlying cost of production, and variations in  $\mu_t$

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<sup>4</sup>Irreversibility of investment would affect this result if the constraint that gross investment cannot be negative is sometimes binding. However, in the present model, gross investment is always chosen to be positive.

would generate fluctuations in  $P_t$  independently of those in  $K_t$  and  $Y_t$ . Another possibility is that the cost of shifting between consumables and new capital goods in the production process does not stay fixed (at unity), and a further idea is that the productivity of old capital might vary stochastically relative to that of new capital.

To capture these types of effects, the price ratio for equity,  $P_{t+1}/P_t$ , is allowed to deviate from that for the capital stock by an independent random term,  $\varepsilon_{t+1}$ :

$$(3) \quad \frac{P_{t+1}}{P_t} = \frac{K_{t+1}}{K_t} + \varepsilon_{t+1}.$$

The shock  $\varepsilon_{t+1}$  is assumed to have zero mean, serial independence, and to be distributed independently of  $K_{t+1}/K_t$ . This specification means that an epsilon shock, possibly representing a change in markups or a shift in the rate of transformation between consumables and capital on the production side, has a permanent effect on the level of the equity price. For asset-pricing purposes, an important condition is that  $\varepsilon_{t+1}$  will be distributed independently of consumption growth,  $C_{t+1}/C_t$  (because  $\varepsilon_{t+1}$  is assumed to be independent of capital-stock growth,  $K_{t+1}/K_t$ ). In this case, the epsilon shock will not influence asset pricing in the model's baseline specification but will allow for the equity price to be more volatile than capital stock and output.

The model allows for rare disasters by having stochastic depreciation of the capital stock; that is, destruction of trees. The capital stock evolves because of gross investment and depreciation,  $\delta_{t+1}K_t$ :

$$(4) \quad K_{t+1} = K_t + I_t - \delta_{t+1}K_t.$$

The depreciation rate,  $\delta_{t+1}$ , is stochastic and equal to

$$(5) \quad \delta_{t+1} = \delta + u_{t+1} + v_{t+1},$$

where  $0 < \delta < 1$ . The  $u_{t+1}$  shock, normally distributed with mean 0, variance  $\sigma^2$ , and serial independence, represents normal economic fluctuations. This shock has a permanent effect on

depreciation and, therefore, on the level of the capital stock. (Since  $u_{t+1}$  can be negative, it is possible that  $\delta_{t+1}$  would be negative.) The  $v_{t+1}$  shock represents rare disasters, modeled as large-scale destruction of trees. With probability  $1-p$ ,  $v_{t+1}=0$ , and with probability  $p$ ,  $v_{t+1}=-d_{t+1}$ ; that is, the fraction  $d_{t+1}$  ( $0 < d_{t+1} < 1$ ) of the trees is (permanently) destroyed in a disaster event. The disaster size,  $d_{t+1}$ , is subject to a time-invariant probability distribution. (This disaster shock is one-sided because there are no bonanzas associated with the sudden appearance of new trees.) A natural extension, as in Gabaix (2012), would allow for stochastic variations in disaster probability,  $p$ , or in the distribution of disaster sizes,  $d$ .

One part of tree output is paid out as dividends, which correspond to consumption of fruit by owners. The other part is retained within the tree business to finance investment in new trees. From the standpoint of equity holders, the first part of the return on equity is the dividend yield, which equals the ratio of consumption,  $C_t$ , to the capital stock,  $K_t$ .<sup>5</sup> The second part consists of equity price appreciation,  $P_{t+1}/P_t$ , given in equation (3). Therefore, using equation (2), the gross one-period return on equity,  $R_t^e$ , is

$$(6) \quad R_t^e = \frac{C_t}{K_t} + \frac{K_{t+1}}{K_t} + \varepsilon_{t+1} = A - \frac{I_t}{K_t} + \frac{K_{t+1}}{K_t} + \varepsilon_{t+1}.$$

Equations (4) and (5) imply that the growth of the capital stock is given by

$$(7) \quad \frac{K_{t+1}}{K_t} = 1 + \frac{I_t}{K_t} - \delta - u_{t+1} - v_{t+1}.$$

Substitution of equation (7) into the right-hand side of equation (6) yields:

$$(8) \quad R_t^e = 1 + A - \delta - u_{t+1} - v_{t+1} + \varepsilon_{t+1},$$

so that the net rate of return,  $r_t^e = R_t^e - 1$ , is

$$(9) \quad r_t^e = A - \delta - u_{t+1} - v_{t+1} + \varepsilon_{t+1}.$$

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<sup>5</sup>With a markup ratio  $1+\mu$ , the dividend payout in value terms is  $(1+\mu) \cdot C_t$  and the equity price is  $(1+\mu) \cdot K_t$ . Therefore, a change in  $\mu$  does not affect the dividend yield.

In equation (9), the shocks  $u_{t+1}$  and  $\varepsilon_{t+1}$  have zero mean, and the disaster shock  $v_{t+1}$  has mean  $p \cdot E(d)$ . Therefore, the expectation of the one-period net rate of return is

$$(10) \quad E(r_t^e) = A - \delta - p \cdot E(d).$$

An assumption is that  $A > \delta + p \cdot E(d)$  and, hence,  $E(r_t^e) > 0$ . Since productivity,  $A$ , disaster probability,  $p$ , and mean disaster size,  $E(d)$ , are time invariant,  $E(r_t^e)$  is constant over time.

The next step concerns the determination of the ratio of gross investment to the capital stock,  $I/K_t$ . Gross investment equals gross saving (for a closed economy with no government sector) and can be determined from dynamic conditions for consumer optimization.

Barro (2009) uses a specification of preferences for the representative consumer based on the analysis of Epstein and Zin (1989) and Weil (1990), described as EZW preferences. This specification, corresponding to Barro (2009, equation [10]), features constant values of the rate of time preference,  $\rho$ , the coefficient of relative risk aversion,  $\gamma$ , and the intertemporal elasticity of substitution ( $IES$ ),  $1/\theta$ , where  $\theta = \gamma$  holds in the standard power-utility formulation. The condition  $\gamma > 1$  is required for the model to have a chance of generating an equity premium in the neighborhood of that observed empirically. In that case, the standard representation would require  $\theta > 1$  and, hence,  $IES < 1$ . Barro (2009) followed Bansal and Yaron (2004) to argue that the property  $IES < 1$  generates counter-factual predictions regarding equity pricing. In the present analysis,  $\gamma > 1$  is crucial, but  $\theta < 1$  is less important.

In general, EZW preferences do not allow for simple formulas for pricing assets. However, when the underlying shocks are i.i.d., as in the present model, the analysis simplifies dramatically. Specifically, Barro (2009, equations [12] and [13]) used results from Giovannini and Weil (1989, appendix) to show that a standard-looking asset-pricing condition applies:

$$(11) \quad C_t^{-\gamma} = \left( \frac{1}{1 + \rho^*} \right) \cdot E_t(R_t \cdot C_{t+1}^{-\gamma}),$$

where  $R_t$  is the gross return on any asset between dates  $t$  and  $t+1$ . Two features that differ from those in the standard power-utility model (where  $\gamma=\theta$ ) are worth noting. First, the exponents on  $C_t$  and  $C_{t+1}$  in equation (11) involve  $\gamma$ , the coefficient of relative risk aversion, not  $\theta$ , which is the reciprocal of the *IES*. Second, the effective rate of time preference,  $\rho^*$ , differs from  $\rho$  when  $\gamma$  and  $\theta$  diverge. The formula for  $\rho^*$  is, if  $\gamma \neq 1$ ,

$$(12) \quad \rho^* = \rho - (\gamma - \theta) \cdot \left\{ E(g_t) - \left(\frac{1}{2}\right) \cdot \gamma \sigma^2 - \left(\frac{p}{\gamma-1}\right) \cdot [E(1-d)^{1-\gamma} - 1 - (\gamma-1) \cdot Ed] \right\}.$$

The term  $E(g_t)$  is the economy's expected growth rate and is derived below.

Because the shocks  $u_{t+1}$  and  $v_{t+1}$  are i.i.d. (permanent to the levels of capital stock and output), the ratio of gross saving to the capital stock will be optimally chosen as a constant, denoted by  $v$ . The value of  $v$  can be determined by applying the consumption-based asset-pricing formula in equation (11) to the gross return on equity, given in equation (8). The result (applying as the length of the period approaches zero) is:<sup>6</sup>

$$(13) \quad v = \delta + \left(\frac{1}{\theta}\right) \left\{ A - \delta - \rho - \left(\frac{1}{2}\right) \gamma (1 - \theta) \cdot \sigma^2 - p \cdot \left(\frac{1-\theta}{\gamma-1}\right) [E(1-d)^{1-\gamma} - 1] \right\}.$$

Equation (13) implies that, if  $\gamma > 0$ , the sign of the effect of uncertainty ( $\sigma$ ,  $p$ , or the distribution of  $d$ ) on the gross saving ratio,  $v$ , depends on the *IES*,  $1/\theta$ , not the degree of risk aversion,  $\gamma$ . If  $\theta < 1$ , so that the *IES* exceeds 1, the “substitution effect” dominates, and more uncertainty (higher  $\sigma$  or  $p$  or an outward shift of the  $d$ -distribution) decreases  $v$ . For the parameter values used subsequently to calibrate the model (in Table 2), the main effect from

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<sup>6</sup>For equation (13) to be valid, the associated level of consumption has to be positive, corresponding to  $v < A$ . Equation (13) implies that the condition  $v < A$  can be expressed as:

$$\rho > (1 - \theta) \left\{ A - \delta - \left(\frac{1}{2}\right) \gamma \sigma^2 - \left(\frac{p}{\gamma-1}\right) [E(1-d)^{1-\gamma} - 1] \right\}.$$

If this inequality does not hold, the optimization problem is not well defined because the attainable expected utility is unbounded. The inequality is satisfied for the parameter values assumed later. (An analogous inequality condition applies in the standard deterministic neoclassical growth model, where  $\sigma^2$  and  $p$  equal zero.)

uncertainty on the saving ratio comes from disaster risk—the term involving  $p$  on the far right of equation (13). The term involving  $\sigma^2$  in this calibration is quantitatively unimportant.

In the present model, the growth rates of the macroeconomic variables—capital stock, output, and consumption—are always the same. This common growth rate, denoted by  $g_t$ , is given from equation (7) as

$$(14) \quad g_t = \frac{K_{t+1}}{K_t} - 1 = v - \delta - u_{t+1} - v_{t+1},$$

where recall that  $u_{t+1}$  is the normal shock and  $v_{t+1}$  is the disaster shock. A higher gross saving ratio,  $v$ , in equation (13) implies a higher growth rate in equation (14).

The expected growth rate is constant and given from equation (14) by

$$(15) \quad E(g_t) = v - \delta - p \cdot E(d).$$

An assumption is that the parameters imply  $E(g_t) > 0$ , given that  $v - \delta$  is determined from equation (13).

The relationship between the expected rate of return on equity,  $E(r_t^e)$  from equation (10), and the expected growth rate,  $E(g_t)$  from equation (15), is given by

$$(16) \quad E(r_t^e) - E(g_t) = A - v.$$

Therefore, if  $A > v$ —meaning that output exceeds gross investment and, hence, that consumption is positive (see n. 6)—the expected rate of return on equity exceeds the expected growth rate of the economy.<sup>7</sup> In other words, the  $r > g$  condition holds in the model when the  $r$  applies to the expected rate of return on equity.

Consider now the risk-free real interest rate, denoted by  $r^f$ . In the model, risk-free claims are internal instruments, effectively private bonds that correspond to loans from one agent to

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<sup>7</sup>The condition  $A > v$  corresponds to the criterion for dynamic efficiency proposed in Abel, et al. (1989, p.2): “... an economy is dynamically efficient if it invests less than the return to capital ...” In the present model,  $A$  equals the marginal (and average) product of capital and, therefore, corresponds to the gross return on capital.

another.<sup>8</sup> The aggregate of risk-free assets always equals zero; that is, these assets are in zero net supply. A later section considers government bonds, which may be in positive net supply.

Although the aggregate quantity of risk-free assets will be zero, the model still determines a shadow real interest rate,  $r^f$ , applying to these assets. The value of  $r^f$ , which is constant, can be determined from the asset-pricing condition in equation (11) along with the result that  $C_{t+1}/C_t$  equals the value  $g_t$  given in equation (14). The solution is

$$(17) \quad r^f = A - \delta - \gamma\sigma^2 - p \cdot E[d \cdot (1 - d)^{-\gamma}].$$

More uncertainty—higher  $\sigma$  or  $p$  or an outward shift of the  $d$ -distribution—decreases  $r^f$ .<sup>9</sup> For the parameter values used to calibrate the model (in Table 2), the main effect from uncertainty on  $r^f$  comes from the disaster term, which involves  $p$  on the far right of equation (17). With these parameter values, including  $\gamma=3.5$ , and for the observed histogram of disaster sizes, the term  $E[d \cdot (1 - d)^{-\gamma}]$  equals 1.7, implying that a (once-and-for-all) rise in disaster probability,  $p$ , by 0.010 per year lowers  $r^f$  by a substantial 0.017 per year. The effect associated with the normal shock, which involves  $\sigma^2$ , is quantitatively unimportant. Reasonable parameter values accord with a value of  $r^f$  close to or below zero in equation (17). For the values specified in Table 2, the equilibrium  $r^f$  implied by equation (17) is 0.001, essentially zero.<sup>10</sup> By comparison, long-term averages for OECD countries of realized real rates of return on government bills, as shown in Table 1, are around 0.01 per year.

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<sup>8</sup>The assumption is that there do not exist storable goods or other real assets that yield a risk-free real rate of return above the equilibrium  $r^f$  that arises in the model.

<sup>9</sup>Since the model has i.i.d. shocks, the term structure of risk-free rates is flat; that is,  $r^f$  is the short-term and long-term risk-free rate.

<sup>10</sup>This low value of  $r^f$  reflects the fatness of the disaster tail, not the skewness, which arises from the exclusion of bonanzas. Skewness would not apply if there were a bonanza probability,  $q$ , that equaled  $p$  and if the distribution of bonanza sizes were the same as that for disasters. In this case, it turns out that the calibrated model's equilibrium value of  $r^f$  becomes 0.005, rather than 0.001. To put it another way, with a small rise in  $p=q$ , which turns out to be from 0.040 to 0.042, the equilibrium  $r^f$  would still be 0.001, despite the lack of skewness. Skewness is unimportant because, with the substantial “diminishing marginal utility” implied by  $\gamma=3.5$ , the positive tail from bonanzas counts little for the equilibrium  $r^f$ .

The equity premium is given from equations (10) and (17) by

$$(18) \quad E(r_t^e) - r^f = \gamma\sigma^2 + p \cdot E\{d \cdot [(1 - d)^{-\gamma} - 1]\}.$$

For the parameter values specified in Table 2 (which include  $\gamma=3.5$ ), the predicted equity premium from equation (18) is around 0.06 per year. This result accords with measured equity premia, gauged by the gap shown in Table 1 between long-run averages of realized real rates of return on equity and short-term government bills. (The observed stock returns can be adjusted to account for leverage associated with bond financing.) The dominant part of the equity premium in the model reflects disaster risk, which appears in the term in equation (18) that contains the disaster probability,  $p$ . The other part,  $\gamma\sigma^2$ , is quantitatively unimportant, as in the related analysis of the equity-premium puzzle in Mehra and Prescott (1985). Note that, in the model, the positive effect of disaster risk on the equity premium reflects the negative impact on  $r^f$  in equation (17), not an effect on the expected rate of return on equity,  $E(r_t^e)$ , in equation (10).<sup>11</sup>

The relation between  $r^f$  and the expected growth rate,  $E(g_t)$ , is given from equations (17) and (15) by

$$(19) \quad r^f - E(g_t) = A - v - \gamma\sigma^2 - p \cdot E\{d \cdot [(1 - d)^{-\gamma} - 1]\}.$$

The parameter values considered below suggest that the gap in the model between  $r^f$  and  $E(g_t)$  is likely to be negative. This result accords with the result that the model's predicted value for  $r^f$  in equation (17) is likely to be close to zero. In any event, the model does not require the  $r > g$  condition to hold when the  $r$  refers to the risk-free rate. Thus, there is no conflict between the theory and the empirical observation that this condition fails to hold when  $r$  is measured by the average real rate of return on government bills.

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<sup>11</sup>Equation (10) implies a small negative effect from the disaster probability,  $p$ , on  $E(r_t^e)$ . This effect would not arise if bonanzas were treated symmetrically with disasters, as in n. 10.

In terms of portfolio allocation, the representative agent in period  $t$  holds claims on all of the capital stock,  $K_t$ , at price,  $P_t$ , and holds a zero net position in risk-free assets. That is, in the equilibrium—for the distribution of  $r_t^e$  implied by equation (9) and for the value of  $r^f$  given in equation (17)—each agent is willing at all points in time to hold 100% of assets in risky capital and 0% in risk-free claims.

Because the representative agent ends up with a zero net position in risk-free assets, the equilibrium results would be the same if risk-free assets did not exist. However, the existence of these assets would matter if households were heterogeneous; differing, for example, by coefficients of relative risk aversion,  $\gamma$ . In that case, agents with relatively high  $\gamma$  would tend to be net positive in safe assets, thereby lending funds on a risk-free basis to those with relatively low  $\gamma$ .

## II. Illustrative Calibration of the Model

Table 2 shows how the model works quantitatively for a reasonable set of parameter values. The most important settings in the calibration relate to disaster probability and size distribution. The values for disaster probability,  $p$ , and the distribution of disaster sizes,  $d$ , come from an updated version of the numbers in Barro and Ursúa (2008). Specifically, peak-to-trough disaster events of size 10% or more for per capita GDP were isolated for 185 cases, corresponding to data for 40 countries going back as far as 1870 and up to 2012.<sup>12</sup> This sample shows an average proportionate disaster size,  $E(d)$ , of 0.21. Taking account of the duration of each disaster event, the implied disaster probability,  $p$  (the chance of entering into a disaster

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<sup>12</sup>Colombia is the only one of the 40 countries to experience no GDP-based contractions of size 10% or more. Malaysia and Singapore, which have long-term GDP data, were excluded from the calculations because of the large gaps in data around World War II.

state), is 0.04 per year. The objects  $E(1-d)^{-\gamma}$ ,  $E(1-d)^{1-\gamma}$ , and  $E[d((1-d)^{-\gamma})]$  equal 4.0, 2.3, and 1.7, respectively, for a coefficient of relative risk aversion,  $\gamma$ , of 3.5 and for the observed histogram of disaster sizes.<sup>13</sup> This value of  $\gamma$ , when used in equation (17) (along with the value of  $p$  and the size distribution of  $d$ ), generates an equity premium that accords with empirically observed values around 0.06 per year.<sup>14</sup> The variance of the normal shock,  $\sigma^2$ , is set at 0.0004 per year to accord with the observed annual volatility of real GDP growth. However, in the relevant range, the results on the equity premium and other outcomes are insensitive to the value of  $\sigma^2$ .

The deterministic part of the depreciation rate,  $\delta$ , is set at 0.05 per year, the average BEA number from 1948 to 2018 for fixed assets (including government assets but excluding consumer durables other than residential housing). The value set for  $A$ , 0.12 per year, is chosen to generate realistic levels of the real rates of return, which turn out to be 0.062 per year for  $E(r^e)$  and 0.001 per year for  $r^f$ . The values of  $\rho=0.04$  per year and  $\theta=0.5$  determine the gross saving and investment ratio,  $v$ , to be 0.090 per year<sup>15</sup> and the expected growth rate,  $E(g)$ , to be 0.032 per year (the long-run average U.S. growth rate of real GDP).

The implied ratio of gross investment to GDP is  $v/A=0.75$ . An interpretation of this high ratio is that, as mentioned before, the underlying  $AK$  production function should be interpreted in terms of a broad definition of what constitutes capital and investment.

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<sup>13</sup>An alternative approach, pursued in Barro and Jin (2011), assumes that disaster sizes follow a power-law distribution. The results are similar to those based on the observed histogram.

<sup>14</sup>This calculation views each disaster event as permanent for the level of real per capita GDP. Barro, Nakamura, Steinsson, and Ursúa (2013) and Barro and Jin (2020) assume, instead, that disasters are only partly permanent. The estimated eventual recovery fraction is about 50% of the initial contraction. An allowance for the partly temporary nature of macroeconomic disasters raises the value of  $\gamma$  required to match the observed equity premium.

<sup>15</sup>The values of  $\rho$  and  $\theta$  both contribute to  $v$  and  $E(g)$ . The value of  $\theta$  would also affect the sensitivity of the gross saving rate to dimensions of uncertainty— $p$ , the size distribution of  $d$ , and  $\sigma^2$ . However, in the present analysis, these uncertainty parameters are fixed. Therefore, the results shown for outcome variables in Table 2 could be generated with alternative combinations of  $\rho$  and  $\theta$ .

### III. The $r$ - $g$ Conditions

This section elaborates on the  $r$ - $g$  conditions for equity and safe assets. A key issue is whether  $r^f \leq E(g_t)$  violates a transversality condition because it may allow an individual to borrow and roll over debt in perpetuity, so that an individual's consumption could be increased without limit (an outcome that cannot apply in equilibrium).

#### A. $r$ - $g$ for Equity

Equation (16) implies that the expected rate of return on equity exceeds the expected growth rate,  $E(r_t^e) > E(g_t)$ . To get perspective on this result, suppose that  $P_t$  is the price of equity (claims on trees) and  $C_t$  (fruit) is the flow of dividends on this equity. (This discussion neglects the  $\varepsilon_{t+1}$  term in the specification for the change in the equity price in equation [3].) The net rate of return on equity between periods  $t$  and  $t+1$  is

$$(20) \quad r_t^e = \frac{C_t}{P_t} + \frac{P_{t+1}}{P_t} - 1.$$

Suppose, as before, that the equilibrium involves equality between the expected growth rate of the equity price,  $\frac{P_{t+1}}{P_t} - 1$ , and the expected growth rate of the capital stock,  $g_t = \frac{K_{t+1}}{K_t} - 1$ , which equals the expected growth rate of consumption,  $\frac{C_{t+1}}{C_t} - 1$ . In this case, the expected net rate of return on equity is

$$(21) \quad E(r_t^e) = \frac{C_t}{P_t} + E(g_t).$$

Rearranging this condition, assuming  $E(r_t^e) \neq E(g_t)$ , yields a formula for the price-dividend ratio of an equity claim:

$$(22) \quad \frac{P_t}{C_t} = \frac{1}{E(r_t^e) - E(g_t)}.$$

Equation (22) is usually called the “Gordon growth formula.”<sup>16</sup> This formula relates the price-dividend ratio for equity to the reciprocal of the difference between the expected net rate of return on equity and the expected growth rate (of dividends; that is, of  $C_t$  in the present model). Equation (22) implies that  $P_t/C_t$  will be positive and finite only if  $E(r_t^e) > E(g_t)$ , as already noted in equation (16).

Another way to think about the result is that claims on capital give the owners the rights to a stream of dividends (fruit) that is expected to rise at the rate  $E(g_t)$ . If this expected growth rate were at least as high as the discount rate—which corresponds to the expected rate of return on the asset,  $E(r_t^e)$ —then the present value of the claim would be infinite. This result is inconsistent with an equilibrium in which consumption is chosen optimally over time. However, this inconsistency does not arise if  $E(r_t^e) > E(g_t)$ .

## B. $r$ - $g$ for Safe Assets

In contrast to equity shares, risk-free assets are internal claims that are in zero net supply. In the model, the representative agent ends up with a zero net position in these assets. Hence, there is no condition analogous to the Gordon growth formula in equation (22) that would require  $r^f > E(g_t)$ .

It is possible in the model that  $r^f > E(g_t)$  would hold. For example, if there is no uncertainty, so that  $p=\sigma^2=0$ , then  $r^f$  would equal  $E(r_t^e)$ , and both returns would exceed the expected growth rate,  $E(g_t)$ .<sup>17</sup> However, for realistic parameter values, as in Table 2, the condition  $r^f < E(g_t)$  is likely to hold, and this result is consistent with the data in Table 1.

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<sup>16</sup>See Campbell (2018, p. 130). The reference to Gordon refers to Gordon and Shapiro (1956, equation [7]).

<sup>17</sup>This result requires consumption to be positive, which corresponds, in the absence of uncertainty, to  $\rho > (1-\theta)(A - \delta)$ .

Another way to think about the result is to consider the position of the representative agent, who, in the equilibrium, holds all assets as risky equity with a zero net position in safe assets. Suppose that this agent in period  $t$  perturbs his or her position by issuing one unit of safe bonds (borrowing one unit) and using the proceeds to raise  $C_t$  by one unit. Suppose further that the agent plans never to repay this debt; that is, the debt is rolled over in perpetuity, so that the stock of debt grows at the risk-free rate,  $r^f$ . All other parts of the plan for consumption and portfolio allocation subsequent to date  $t$  are assumed to be unchanged (and the time paths of  $r_t^e$  and  $r^r$  are unaffected by an individual's perturbation). If this new plan were feasible, the agent's expected overall utility would rise, corresponding to the increase in  $C_t$  and unchanged values of  $C_{t+1}, \dots$ . That is, the agent would not actually have been optimizing, and the proposed equilibrium would be invalid; in effect, a transversality condition would be violated.

Suppose that, in assessing the feasibility of this kind of perturbation, the key issue is whether an individual's debt can ever exceed the value of the individual's assets. That is, the assets represent collateral, and an excess of debt over collateral is assumed to trigger default, so that the debt issued at time  $t$  cannot actually be safe. In the proposed perturbation from the initial plan, the agent's assets held as claims on capital grow at rate  $g_t$ . Therefore, if  $r^f \leq E(g_t)$ ,<sup>18</sup> the expectation is that the ratio of the debt to these assets will not rise over time, so that collateral would tend to rise (or stay constant) relative to debt. This result might suggest that the perturbation is feasible; however, the argument is invalid because  $g_t$  is subject to uncertainty,

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<sup>18</sup>This argument can be extended to various forms of derivatives, which offer an array of expected rates of return in equilibrium. For example, far-out-of-the-money put options on equity shares would have a particularly low expected rate of return because of the protection offered against disaster outcomes. The high expected rate of return from writing these put options has to be weighed against the high risk—involving a reliance on expected growth to outweigh the cumulated obligation in the long run.

particularly from disaster risk, and this uncertainty cumulates into the future.<sup>19</sup> Specifically, for any  $\varepsilon > 0$ , there is a non-zero probability that income from capital will fall below  $\varepsilon$  and stay there forever; hence, there is a chance that the debt will, at some point, exceed the value of assets held as claims on capital, and this breach of collateral triggers default. If the cost of default is large enough, individuals will be deterred from issuing debt that they plan to roll over forever. In this case, the equilibrium features a zero net position for each individual's holdings of safe assets, and the risk-free real interest rate,  $r^f$ , is the one given in equation (17).

The argument, consistent with that in Abel, et al. (1989, p. 14), is analogous to the one constructed by Samuelson (1969) to counter the view that long-horizon investors would place a particularly large share of assets into risky form—equity rather than safe assets in the present context. The fallacious reasoning is that  $E(r^e) > r^f$  implies that assets held as equity, rather than risk-free bonds, are almost surely worth more at horizon  $T$  when  $T$  is very long. The problem is that the uncertainty associated with long-term asset values cumulates in parallel with  $T$  (as in n. 19), and the tradeoff between risk and expected return does not depend on  $T$  (in the type of i.i.d. model under consideration). In the language of Campbell (2018, p. 270), the model satisfies the conditions for myopic portfolio choice.

The key condition needed to validate the equilibrium is the exclusion of a form of Ponzi or chain-letter finance in which an individual borrows more at the risk-free rate and then fully rolls over the added debt in perpetuity.<sup>20</sup> Individuals can consider an array of perturbations to the equilibrium in which they change the amount consumed in any period  $t$  and then change the

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<sup>19</sup>For example, the variance of the cumulated shocks is proportional to the future date  $T$  for the normal and disaster terms in equation (7).

<sup>20</sup>If this type of Ponzi finance is feasible, then all agents would engage in this practice. In the end, since safe assets are in zero net supply, the representative agent has to end up with a zero net position in these assets. However, the features of the equilibrium with Ponzi finance are unclear.

amount consumed in any other period, such as  $t+1$ , while shifting correspondingly the amounts held in risk-free form during the two periods. That is, shifts in the timing of consumption associated with the rate  $r^f$  are allowed among any periods within a finite horizon. These perturbations away from the equilibrium are not optimal for the individual because equation (17) guarantees that the first-order conditions for intertemporal choices of consumption (associated with  $r^f$ ) are all satisfied.

#### IV. Government Bonds

Let  $B_t$  be the real quantity of government bonds outstanding at the start of period  $t$ . These bonds are assumed to be analogous to the safe short-term bonds that private agents were able to issue. The real interest rate applicable to government bonds is assumed to be  $r^f$ , the same rate as that for private bonds. This assumption of equal interest rates is not far from reality for the United States if one identifies private bonds with prime corporate obligations. For example, from 1920 (which has the first data on securities comparable to U.S. Treasury Bills) to 2019, the average of annual nominal yields was 0.034 for 3-month Treasury Bills and 0.041 for 90-day commercial paper; that is, the spread was only 0.007. The average annual real rate of return on 10-year U.S. government bonds over this period was 0.029, whereas that on Moody's AAA corporate bonds was 0.036, again a spread of 0.007.

The government collects real taxes net of transfers of  $T_t$  during period  $t$ . The quantity  $T_t$  is treated as a random variable. Neglecting government purchases of goods and services (government consumption and investment), the government's budget constraint is:

$$(23) \quad B_{t+1} - B_t = r^f \cdot B_t - T_t.$$

Hence, the budget deficit equals the excess of spending (for interest and transfers) over revenue (from taxes). The real interest rate  $r^f$  is assumed to be constant and known in period  $t$ , as in the model worked out before without a government sector. Net taxes,  $T_{t+j}$ , in each future period ( $j \geq 1$ ) are stochastic from the perspective of period  $t$ , and the evolution of these net taxes determines the future quantities of government bonds,  $B_{t+2}, B_{t+3}, \dots$ . These quantities are random from the perspective of period  $t$ , but the realizations of these quantities is linked to the realizations of net taxes from the government's budget constraint in equation (23).

A key object for the equilibrium is the present value of future net taxes, computed using as a discount rate the safe real interest rate,  $r^f$ . Iterating equation (23) into the future for  $N \geq 1$  periods yields an intertemporal budget constraint for the government:

$$(24) \quad \sum_{j=1}^N [T_{t+j-1}/(1+r^f)^j] = B_t - B_{t+N}/(1+r^f)^N.$$

Therefore, aside from the final term on the right-hand side, the present value of future net taxes, computed as of period  $t$ , is non-stochastic and pinned down to equal the stock of government bonds,  $B_t$ , at the start of period  $t$ .

The previous infinite-horizon model corresponds to  $N$  tending to infinity. A key issue is how the final term on the right-hand side of equation (24),  $B_{t+N}/(1+r^f)^N$ , behaves as  $N$  approaches infinity. The usual perspective is that, asymptotically,  $B_{t+N}$  cannot grow at a rate higher than  $E(g_t)$ , the expected growth rate of real GDP, so that the ratio of public debt to GDP,  $B_{t+N}/Y_{t+N}$ , does not rise in the long run. In that case, the condition  $r^f > E(g_t)$  would ensure  $\frac{B_{t+N}}{(1+r^f)^N} \rightarrow 0$  as  $N \rightarrow \infty$ . However, the previous analysis found that  $r^f \leq E(g_t)$  could apply asymptotically.

The asymptotic behavior of the term  $B_{t+N}/(1+r^f)^N$  is analogous to the Ponzi-type borrowing considered for an individual agent in the model without government. That is, the

question is whether the government can borrow an additional unit at date  $t$  and then allow the debt to roll over forever at the rate  $r^f$  without ever repaying principal or interest. In the earlier setting, this possibility was ruled out, even when  $r^f \leq E(g_t)$ , because of the uncertainty in the evolution of real GDP and, hence, in the value of an individual agent's assets (collateral) held as claims on capital. That is, there was a positive probability that the amount owed would eventually exceed an agent's collateral, thereby triggering default.

In the context of the government, the collateral relates to taxing capacity, which, in a richer model, would depend on the economy's real GDP. Uncertainty in the evolution of GDP implies that the rolling over forever of the government's debt generates a positive probability that the debt would eventually exceed the government's collateral, thereby triggering sovereign default. In this case, Ponzi borrowing in risk-free form by the government can be ruled out, and equation (24) becomes, when expressed over an infinite horizon:

$$(25) \quad \sum_{j=1}^{\infty} [T_{t+j-1} / (1 + r^f)^j] = B_t.$$

Equation (25) says that the government can choose the timing of tax collections (and, therefore, budget deficits), but the present value of taxes is pinned down to equal the starting amount of public debt.

The model described before still applies for private agents. The only new elements are that the representative agent holds the initial stock of government bonds,  $B_t$ , and has to pay the stream of (lump-sum) net taxes,  $T_t, T_{t+1}, \dots$ . However, the present value of the latter over an infinite horizon (evaluated at the rate  $r^f$ ) is pinned down from equation (25) to equal  $B_t$ . Therefore, the net wealth of an individual agent is unaffected by the level of  $B_t$  or the timing of taxes and budget deficits. It follows that the model satisfies Ricardian Equivalence—the

equilibrium with respect to real rates of return, investment, and economic growth is invariant with choices related to public debt.

Another way to look at the results is in terms of quantities of safe assets. Government bonds,  $B_t$ , are a form of safe asset, which pays the safe real interest rate,  $r^f$ . However, net taxes owed to the government amount to a safe (that is, certain) liability—although the timing of taxes is uncertain, the overall obligation has a fixed present value when evaluated using the rate  $r^f$ . Equation (25) implies that the net of the asset and liability is nil, implying no change in the economy's net quantity of safe assets. In this sense, the introduction of public debt does not mean that safe assets are in positive net supply.

The model can be extended to allow for a path of government purchases,  $G_t$ . Future values  $G_{t+1}$ ,  $G_{t+2}$ , ... are stochastic from the perspective of period  $t$ . These choices might reflect war and peace, changing preferences for public programs, and so on. If Ponzi finance by the government is still ruled out, the government's intertemporal budget constraint over an infinite horizon in equation (25) becomes:

$$(26) \quad \sum_{j=1}^{\infty} [T_{t+j-1}/(1+r^f)^j] = B_t + \sum_{j=1}^{\infty} [G_{t+j-1}/(1+r^f)^j].$$

Equation (26) implies that the present value of taxes is no longer pegged to equal  $B_t$ . Instead, as time evolves, the changing present value of taxes (above  $B_t$ ) reflects randomness in the present value of government purchases.

The equilibrium of the economy depends on the realization of  $G_t$ , the stochastic process that generates future values  $G_{t+1}$ ,  $G_{t+2}$ , ... and the ways that government purchases affect household utility or production. The equilibrium also takes into account that  $G_t$  adds to  $C_t$  and  $I_t$  as a use of current output,  $Y_t$ . However, Ricardian Equivalence concerns effects from changes in public debt and taxes for a given behavior of government purchases. That is, the issue is how the

economy responds to variations in  $B_t$  and the path of taxes (and budget deficits), for a given path of  $G_t, G_{t+1}, \dots$ . In equation (26), the probability distribution of the present value  $\sum_{j=1}^{\infty} [G_{t+j-1}/(1+r^f)^j]$  is held fixed in this experiment, and the changes related to public debt still have no impact on the net of  $B_t$  over the present value of taxes,  $\sum_{j=1}^{\infty} [T_{t+j-1}/(1+r^f)^j]$  (although this net term is now random and does not equal zero). Therefore, as in the model that excluded government purchases, these fiscal changes have no effect on the net wealth of the representative agent, and Ricardian Equivalence holds.

## V. Summary Observations

The empirical pattern for several OECD countries back as far as 1870 indicates that the familiar dynamic efficient condition  $r > g$  holds when  $g$  is the average growth rate of real GDP if  $r$  is the average real rate of return on equity,  $r^e$ . The condition does not hold if  $r$  is the risk-free rate,  $r^f$ , proxied by the average real rate of return on Treasury Bills. This pattern accords with a simple disaster-risk model calibrated to fit observed equity premia. The model features stochastic depreciation of capital, with the potential for disaster events in which large portions of capital are destroyed. Alternative versions of this model that could be considered feature productivity shocks, shifts in the relative cost of producing new capital goods, changes in the value (productivity) of old capital, and variations in markup ratios.

As long as Ponzi-type finance for private agents and the government are precluded, the equilibrium can feature a risk-free rate,  $r^f$ , below the expected growth rate,  $E(g)$ , and possibly close to zero. (The model assumes that there do not exist real assets that deliver a positive, safe real rate of return.) The result  $r^f \leq E(g)$  does not signal dynamic inefficiency. In contrast, the inequality  $E(r^e) > E(g)$  is required for dynamic efficiency, implied by the model, and consistent

with the data. The model satisfies Ricardian Equivalence for public debt because, with Ponzi finance by the government excluded, a rise in safe assets from increased government bonds is matched by an increase in the safe (that is, certain) present value of liabilities associated with net taxes.

**Table 1****Long-Term Rates of Return and Growth Rates for 14 OECD Countries**

| <b>Country</b>        | <b>Stock<br/>return</b> | <b>Bill<br/>return</b> | <b>Govt. bond<br/>return</b> | <b>Growth rate of:</b>    |                         |                   |
|-----------------------|-------------------------|------------------------|------------------------------|---------------------------|-------------------------|-------------------|
|                       |                         |                        |                              | <b>GDP per<br/>capita</b> | <b>C per<br/>capita</b> | <b>Population</b> |
| <b>Australia</b>      | 0.087                   | 0.012                  | 0.033                        | 0.016                     | 0.015<br>(1902)         | 0.018             |
| <b>Canada</b>         | 0.075                   | 0.013<br>(1900)        | 0.034                        | 0.020<br>(1871)           | 0.018<br>(1872)         | 0.016             |
| <b>Denmark</b>        | 0.058<br>(1874)         | 0.029                  | 0.040                        | 0.018                     | 0.015                   | 0.007             |
| <b>France</b>         | 0.065                   | -0.008                 | 0.008                        | 0.018                     | 0.015                   | 0.004             |
| <b>Germany</b>        | 0.053                   | -0.012                 | 0.015*                       | 0.021                     | 0.018                   | 0.005             |
| <b>Italy</b>          | 0.061<br>(1925)         | 0.003                  | 0.016                        | 0.019                     | 0.016                   | 0.005             |
| <b>Japan</b>          | 0.082<br>(1886)         | 0.004<br>(1883)        | 0.023<br>(1871)              | 0.026<br>(1871)           | 0.024<br>(1875)         | 0.009             |
| <b>Netherlands</b>    | 0.069<br>(1900)         | 0.011                  | 0.028                        | 0.018                     | 0.018                   | 0.011             |
| <b>New Zealand</b>    | 0.076                   | 0.023<br>(1923)        | 0.033                        | 0.014                     | 0.012<br>(1879)         | 0.016             |
| <b>Norway</b>         | 0.061**<br>(1915)       | 0.016                  | 0.030                        | 0.021                     | 0.018                   | 0.007             |
| <b>Sweden</b>         | 0.080<br>(1871)         | 0.023                  | 0.028                        | 0.022                     | 0.020                   | 0.006             |
| <b>Switzerland</b>    | 0.068<br>(1914)         | 0.010<br>(1895)        | 0.020<br>(1900)              | 0.014                     | 0.014                   | 0.008             |
| <b>United Kingdom</b> | 0.065                   | 0.016                  | 0.026                        | 0.015                     | 0.014                   | 0.005             |
| <b>United States</b>  | 0.083                   | 0.012                  | 0.028                        | 0.021                     | 0.018                   | 0.014             |
| <b>Means</b>          | 0.070                   | 0.011                  | 0.026                        | 0.019                     | 0.017                   | 0.009             |

### Notes to Table 1

Stock return refers to broad stock-market indexes and includes dividends. Bill return refers to short-term securities analogous to 3-month Treasury Bills. Bond return refers to government bonds, typically with maturity around ten years. *C* refers to personal consumer expenditure.

Sample periods are 1870-2019 for annual real rates of return, 1870-2017 for annual growth rates of per capita GDP and consumer expenditure, and 1880-2019 for population growth, unless a different starting date for a variable is indicated in parentheses. Rates of return are calculated arithmetically from nominal total returns divided by consumer price indexes. Data on total nominal returns (including dividends paid on stocks) and consumer price indexes are mostly from *Global Financial Data*. See the discussion of an earlier version of these data in Barro and Ursúa (2008, Table 5). The long-term data on macroeconomic variables are updated versions of those described in Barro and Ursúa (2008), available at [scholar.harvard.edu/barro](http://scholar.harvard.edu/barro).

The samples are based on availability of long-term data for rates of return and macroeconomic variables. Countries with long-term information that could not be used include Belgium and Finland (missing information on consumer price indexes), Portugal (missing data on stock returns and consumer price indexes), and Spain (missing data on stock returns, government bond returns, and consumer price indexes).

For U.K. consols, the average real rate of return for 1870-2015 was 0.035. For U.S. high-grade corporate bonds, the average real rate of return for 1870-2019 was 0.038. These results are based on information in *Global Financial Data*.

\*Excludes 1923.

\*\*Based on stock-market index and estimated dividend yield, rather than a total-return index.

**Table 2**  
**Baseline Calibration of Model**

| <b>Parameter</b>                                                        | <b>Value</b> |
|-------------------------------------------------------------------------|--------------|
| Coefficient of relative risk aversion, $\gamma$                         | 3.5          |
| Reciprocal of $IES$ , $\theta$                                          | 0.5          |
| Rate of time preference, $\rho$ (per year)                              | 0.04         |
| Productivity, $A$ (per year)                                            | 0.12         |
| Depreciation rate, $\delta$ (per year)                                  | 0.05         |
| $E(d)$ (mean of disaster size for depreciation)                         | 0.21         |
| $E(1-d)^{-\gamma}$ (based on observed histogram of disaster sizes)      | 4.0          |
| $E(1-d)^{1-\gamma}$ (based on observed histogram of disaster sizes)     | 2.3          |
| $E[d((1-d)^{-\gamma})]$ (based on observed histogram of disaster sizes) | 1.7          |
| $p$ (disaster probability for depreciation, per year)                   | 0.04         |
| $\sigma^2$ (variance of normal shock to depreciation, per year)         | 0.0004       |
| <b>Implied outcome variables in model</b>                               |              |
| $E(r^e)$ (expected unlevered rate of return on equity, per year)        | 0.062        |
| $r^f$ (risk-free real interest rate, per year)                          | 0.001        |
| $v$ (gross saving ratio, $I/K$ , per year)                              | 0.090        |
| $E(g)$ (expected growth rate, per year)                                 | 0.032        |

Notes:

The disaster probability,  $p$ , and the distribution of disaster sizes,  $d$ , come from an updated version of the numbers in Barro and Ursúa (2008). Peak-to-trough contractions of real per capita GDP of 10% or more were isolated for 185 cases, corresponding to data for 40 countries going back as far as 1870 and up to 2012. For this sample, the average proportionate disaster size,  $E(d)$ , is 0.21 and the disaster probability,  $p$  (the chance of entering into a disaster state), is 0.040 per year. The objects  $E(1-d)^{-\gamma}$ ,  $E(1-d)^{1-\gamma}$ , and  $E[d((1-d)^{-\gamma})]$  equal 4.0, 2.3, and 1.7, respectively, based on the histogram for observed disaster sizes and for a coefficient of relative risk aversion,  $\gamma$ , of 3.5. This value of  $\gamma$  generates an equity premium of 0.061 per year, close to that observed empirically. The variance of the normal shock,  $\sigma^2$ , is set at 0.0004 per year to accord with the observed annual volatility of real GDP growth. The deterministic part of the depreciation rate,  $\delta$ , equals 0.05 per year, the average BEA number for the depreciation rate from 1948 to 2018 for fixed assets (including government assets but excluding consumer durables other than residential housing). The value for  $A$ , 0.12 per year, generates realistic levels of real rates of return, 0.062 per year for  $E(r^e)$  and 0.001 per year for  $r^f$ . The values  $\rho=0.04$  per year and  $\theta=0.5$  determine the gross saving and investment ratio,  $v$ , to be 0.090 per year and the expected growth rate,  $E(g)$ , to be 0.032 per year (the long-run average growth rate of U.S. real GDP).

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