Intergenerational Insurance*

Francesco Lancia[1], Alessia Russo[2], and Tim Worrall[3]

[1] *Ca' Foscari University of Venice and the Centre for Economic Policy Research*

[2] *University of Padua and the Centre for Economic Policy Research*

[3] *University of Edinburgh*

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Abstract

How should successive generations insure each other when the enforcement of transfers between generations is limited? This paper studies intergenerational insurance when transfers maximize the expected discounted utility of all generations subject to a participation constraint for each generation. If complete insurance is not achievable, the optimal intergenerational insurance is history-dependent even when the environment is stationary. The risk from a generational shock is spread into the future, with periodic *resetting*. Interpreting intergenerational insurance in terms of public debt, the fiscal reaction function is non-linear and the risk premium on debt is lower than the risk premium with complete insurance.

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1 Introduction

Countries face economic shocks that result in unequal exposure to risk across generations. The Financial Crisis of 2008 and the Covid-19 pandemic are two recent and notable examples.[1] Confronted with such shocks, it is desirable to share risk across generations. However, full risk sharing is not sustainable if it commits future generations to transfers they would not wish to make once they are born. The issue of the sustainability of intergenerational insurance is becoming increasingly relevant in many advanced economies as the relative standard of living of the younger generation has worsened in recent decades.[2] If this generational shift persists, then future generations may be less willing to contribute to insurance arrangements than in the past. Therefore, a natural question to ask is, how should an optimal intergenerational insurance arrangement be structured when there is limited enforcement of risk-sharing transfers?

Despite its policy relevance, this question has not been fully addressed by the literature on intergenerational insurance. The normative approach in the literature investigates the optimal design of intergenerational insurance but neglects the limited enforcement of risk-sharing transfers by assuming that transfers are mandatory. Meanwhile, the positive approach highlights the political limits to intergenerational insurance, while considering equilibrium allocations supported by a particular voting mechanism that are not necessarily Pareto optimal.

In this paper, we examine optimal intergenerational insurance when the enforcement of risk-sharing transfers is limited. Limited enforcement is modeled by assuming that transfers satisfy a participation constraint for each generation. This can be interpreted as requiring that the insurance arrangement be supported by each generation if put to a vote. An arrangement of risk-sharing transfers is *sustainable* if it satisfies the participation constraint of every generation. *Optimal* sustainable intergenerational insurance is determined by a benevolent social planner who chooses transfers to maximize the expected discounted utility of all generations subject to the participation constraints.

The model is simple. At each date, a new generation is born and lives for two periods. Each generation is composed of a single agent, who receives an endowment of a single, non-storable consumption good, both when young and old. Endowments are stochastic with both an idiosyncratic (individual generation) shock and an aggregate growth shock. We adopt the approach of Alvarez and Jermann (2001) and Krueger and Lustig (2010) and assume that preferences

[1] Glover et al. (2020) find that the Financial Crisis of 2008 had a greater negative impact on the older generation, while the young benefited from the fall in asset prices. Glover et al. (2021) find that younger workers have been impacted to a greater extent by the response to the Covid-19 pandemic because they disproportionately work in sectors that have been particularly adversely affected, such as retail and hospitality.

[2] Part A of the Supplementary Appendix reports the changes in the relative standard of living of the young and the old for six OECD countries using data from the Luxembourg Income Study Database.

exhibit a constant coefficient of relative risk aversion (for simplicity, we concentrate on the case of logarithmic preferences) and that the growth and idiosyncratic shocks are independent and identically distributed. In this setting, the underlying economy is stationary. In our baseline model, there are only two frictions. First, risk may not be allocated efficiently, even if the economy is dynamically efficient, because there is no market in which the young can share risk with previous generations (see, for example, Diamond, 1977). Second, the amount of risk that can be shared is limited because transfers between generations cannot be enforced. In particular, the old will not make a transfer to the young (since the old have no future) and the young will only make a transfer to the old if the promise made to them for their old age at least matches their expected lifetime utility from autarky and they anticipate that the promise will be honored by the next generation.

It is well known (see, for example, Aiyagari and Peled, 1991) that if endowments are such that the young wish to defer consumption to old age at a zero net interest rate, then there are stationary transfers that improve upon autarky (Proposition 2). Under this condition, and provided that the first-best transfers cannot be sustained, we find that there is a trade-off between efficiency and providing incentives for the young to make transfers to the old. This trade-off is resolved by linking the utility that the young are promised for their old age to the promise made to the young of the previous generation. The resulting optimal sustainable intergenerational insurance arrangement is history dependent, even though the environment itself is stationary.

To understand why there is history dependence, suppose that the first-best transfers would violate the participation constraint of the young in some endowment state. To ensure that the current transfer made by the young is voluntary, either the current transfer is reduced below the first-best level, or the promised transfers for their old age are increased. Both changes are costly since a smaller current transfer reduces the amount of risk shared today, while increasing the transfers promised to the current young for their old age tightens the participation constraints of the next generation and reduces the risk that can be shared tomorrow. Therefore, there is an optimal trade-off between reducing the current transfer and increasing the future promise. This trade-off depends both on the current endowment and the current promise. For example, consider some current endowment and current promise such that the future promise for the same endowment share is above the current one. If the same endowment state is repeated in the subsequent period, then the young in that period are called upon to make a larger transfer, which in turn requires a higher promise of future utility to them as well. Thus, the transfer depends not only on the current endowment but also on the past promise and hence, the history of endowment shocks.

The optimal sustainable intergenerational insurance is found by solving a functional equation derived from the planner's maximization problem. The solution is characterized by policy functions for the consumption of the young (or equivalently, the transfer made to the old) and the future promised utility for their old age in each endowment state. Both policy functions depend on the current endowment and the current promise. For a given endowment, the consumption of the young is weakly decreasing in the current promise, while the future promise is weakly increasing in the current promise (Lemmas 2 and 3). The policy function for the future promise when the current endowment state is repeated has a unique fixed point that is (ignoring a boundary condition) equal to the utility at the first-best outcome. Therefore, the future promised utility is higher than the current promise when the current promise is less than the corresponding fixed point and it is lower than the current promise when the current promise is greater than the fixed point. When the promised utility is sufficiently low, there is some endowment state in which the participation constraint of the young does not bind. In that case, the future promise is *reset* to the largest value that maximizes the planner's payoff.

The presence of participation constraints means that risk affecting one generation is spread to future generations. The resetting property shows that the effect of such a shock does not however last forever. Moreover, it implies strong convergence to a unique invariant distribution (Proposition 5). Provided that some transfers, though not the first best, can be sustained, the invariant distribution exhibits history dependence and consumption fluctuates across states and over time, even in the long run. This is in stark contrast to the situation under either full enforcement of transfers or no risk. In the former case, the promised utility is constant over time, except possibly in the initial period (Proposition 3). In the latter case, the promised utility is constant in the long run, although there may be a finite initial phase during which the promised utility falls (Proposition 4). In either case, there is no inefficiency in the long run. Thus, *both* risk and limited enforcement are necessary for there to be history dependence and inefficiency in the long run.

Transfers to the old can be interpreted in terms of debt. This allows us to address the dynamics of debt together with the valuation and sustainability of debt. With this interpretation, the planner balances the budget by issuing one-period state-contingent bonds at the state price determined by the corresponding intertemporal marginal rate of substitution and taxing or subsidising the young. Given the bond prices and taxes, the young buy the correct quantity of state-contingent bonds to finance their optimal old-age consumption. This interpretation has several implications. First, with logarithmic preferences, there is a debt policy function that determines the next-period debt as a function of the current debt and the next-period endowment share, where debt is measured relative to the endowment of the young. The debt policy function is constant if debt is low, but it is strictly increasing if debt is above a critical threshold (Corollary 1). This debt policy function, together with the history of endowments, determine the dynamics of debt. Debt rises or falls depending on the evolution of the endowments, but eventually it is reset to a low level, creating cycles of debt. Secondly, the taxes levied by the planner generate a fiscal reaction function, which measures how the tax rate depends on debt. Absent enforcement frictions, the fiscal reaction function is increasing linearly in debt. However, with enforcement fictions, while the fiscal reaction function is increasing and linear for low levels of debt, it is non-linear for higher levels of debt. This non-linearity arises because, above the critical threshold, higher debt raises the quantity of bonds issued, but also lowers the price. Thirdly, there are implications for asset pricing. Yields increase with debt. The long-short spread is positive when debt is low and the young are poor but negative when debt is high and the young are rich (Proposition 6). Finally, since debt provides insurance, the risk premium on debt is below the risk premium on the aggregate endowment (Proposition 7), suggesting that enforcement frictions lower the risk premium on debt.

In an example with two endowment states, we provide a closed-form solution for the bound on the variability of the implied yields and show that the invariant distribution of promised utility (debt) is a transformation of a geometric distribution (Proposition 8). Numerically, the solution can be found using a simple shooting algorithm without the need to solve a functional equation. We also consider the impact of a one-off demographic shock which increases the population of young agents. With limited commitment, the effect of the shock is persistent affecting subsequent generations of agents. That limited enforcement frictions may have persistent and amplifying effects is well known from the literature (see, for example, Cooley et al., 2004).

Literature. The paper builds on the literature of risk sharing in overlapping generations models. In most of this literature transfers are mandatory and consideration is restricted to stationary transfers (see, for example, Shiller, 1999, Rangel and Zeckhauser, 2001), in contrast to the voluntary and history-dependent transfers considered here. Our result on history dependence is foreshadowed in a mean-variance setting by Gordon and Varian (1988), who establish that any time-consistent optimal intergenerational risk-sharing agreement is non-stationary. Ball and Mankiw (2007) analyze risk sharing when generations can trade contingent claims before they are born. They find that idiosyncratic shocks are spread equally across generations and consumption follows a random walk (as in Hall, 1978). Such an allocation is not sustainable since it violates the participation constraint of some future generation almost surely. In contrast, we show that although the effects of a shock can be persistent, they are unevenly spread across future generations and resetting ensures that they cannot last forever.

By interpreting the transfer to the old as public debt, we complement the large literature on debt sustainability and the fiscal reaction function that began with Bohn (1995, 1998). We find that the fiscal reaction function is non-linear when risk sharing is limited by the participation constraints. Many authors (see, for example, Mendoza and Ostry, 2008, Ghosh et al., 2013) have addressed the issue of the non-linearity of the fiscal reaction function but the empirical evidence is mixed. Moreover, since debt provides partial insurance, the risk premium on debt is lower than the risk premium on aggregate risk, suggesting that debt can be sustained even when the expected value of future primary surpluses discounted at the risk-free rate is low, an issue addressed by Bhandari et al. (2017), Jiang et al. (2021), Brunnermeier et al. (2022) and Reis (2022), among many others.

Methodologically the paper is related to the literature on risk sharing and limited commitment with infinitely-lived agents. Two polar cases have been examined: one with two infinitely-lived agents (see, for example, Thomas and Worrall, 1988, Chari and Kehoe, 1990, Kocherlakota, 1996) and the other with a continuum of infinitely-lived agents (see, for example, Thomas and Worrall, 2007, Krueger and Perri, 2011, Broer, 2013). The overlapping generations model considered here has a continuum of agents but only two agents are alive at any point in time. The model is not nested in either of the two infinitely-lived agent models but fills an important gap in the literature by providing an analysis of optimal intergenerational insurance with limited commitment. Here we establish strong convergence to the invariant distribution, whereas Krueger and Perri (2011) and Broer (2013) consider the solution only at an invariant distribution and Thomas and Worrall (2007) discuss convergence only in a special case.

Plan of paper. Section 2 sets out the model. Section 3 considers two benchmarks: one with full enforcement of transfers from the young to the old and the other without risk. Section 4 characterizes the optimal sustainable intergenerational insurance and Section 5 establishes convergence to an invariant distribution on a countable ergodic set. Section 6 provides an interpretation of the optimum in terms of debt and the implications for the fiscal reaction function. Section 7 discusses the asset pricing implications and Section 8 considers the implications for debt valuation. Section 9 presents an example with two endowment states and considers some comparative static properties. Section 10 concludes. The Online Appendix contains the proofs of the main results. Additional proofs and further details can be found in the Supplementary Appendix.

2 The Model

Time is discrete and indexed by $t = 0, 1, 2, \ldots, \infty$. The model consists of a pure exchange economy with an overlapping generations demographic structure. At each time t, a new generation is born and lives for two periods. Each generation is composed of a single agent.[3] The agent is young in the first period of life and old in the second. The economy starts at $t = 0$

[3] Equivalently, we can assume there is a unit mass of identical agents in each generation. The assumption that there is a representative agent in each generation makes it possible to focus on intergenerational risk sharing. By doing so, however, we ignore questions about inequality within generations and its evolution over time.

with an initial old agent and an initial young agent. Since time is infinite, the initial old agent is the only agent that lives for just one period.

At each time t, agents receive an endowment of a perishable consumption good. Endowments are finite and strictly positive. The endowments of the young and the old at time t are e_t^y and e_t^o with an aggregate endowment of $e_t = e_t^y + e_t^o$. The endowment *share* of the young is $s_t := e_t^y / e_t$ (the endowment share of the old is $1 - s_t$) and the gross *growth* rate of the aggregate endowment is $\gamma_t := e_t / e_{t-1}$. There is both idiosyncratic (share of the endowment) and aggregate (growth) risk. The sequences of random variables $(s_t : t \geq 0)$ and $(\gamma_t : t \geq 0)$ take values in finite sets $\mathcal{I}$ and $\mathcal{J}$ respectively where $|\mathcal{I}| = I \geq 2$ and $|\mathcal{J}| = J \geq 1$. The pair $\rho_t := (s_t, \gamma_t)$ taking values in $\mathcal{P} \subseteq \mathcal{I} \times \mathcal{J}$ follows a time-homogenous, aperiodic, finite-state Markov process with the probability of transiting from ρ_t to state ρ_{t+1} next period given by $\varpi(\rho_t, \rho_{t+1})$.

Denote the history of endowment shares and growth rates up to and including time t by $s^t := (s_0, s_1, ..., s_t) \in \mathcal{I}^t$ and $\gamma^t := (\gamma_0, \gamma_1, ..., \gamma_t) \in \mathcal{J}^t$ and let $\rho^t := (\rho_0, \rho_1, ..., \rho_t) \in \mathcal{P}^t$. The distribution of ρ_0 is given by the function $\varpi(\rho_0)$ and the probability of reaching history ρ^t is $\varpi(\rho^t) = \varpi(\rho^{t-1})\varpi(\rho_{t-1}, \rho_t)$. Hence, the aggregate endowment at time t is the random variable $e_t = \prod_{k=0}^t \gamma_k$ with $\gamma_0 = e_0$.

There is complete information: all information about endowments and the probability distribution is public. Endowments depend only on the current state whereas consumption can, in principle, depend on the history of states. Denote the per-period consumption of the young by $C(\rho^t)$ and the corresponding consumption share by $c(\rho^t) = C(\rho^t)/e_t$. There is no technology for saving or investment and hence, the aggregate endowment is consumed each period. Therefore, the per-period consumption of the old is $e_t - C(\rho^t)$ and the corresponding consumption share is $1 - c(\rho^t)$. In autarky, agents consume only their own endowments, that is, the consumption share of the young is s_t and the consumption share of the old is $1 - s_t$ for all t and (ρ^{t-1}, ρ_t).

Each generation is born after that period's uncertainty is resolved when the growth rate of the economy and the endowment shares of the young and the old are known. Therefore, after birth, a generation only faces uncertainty in old age and there is no insurance market in which the young can insure against their endowment risk. Let $\{C\} = \{C(\rho^t) : t \geq 0, \rho^t \in \mathcal{P}^t\}$ denote a history-contingent consumption stream of the young. Then, the lifetime utility gain over autarky for a generation born after the history ρ^t is:

$$U\left(\{C\}; \rho^t\right) := u(C(\rho^t)) - u(e_t^y) + \beta \sum_{\rho_{t+1}} \varpi(\rho_t, \rho_{t+1}) \left(u(e_{t+1} - C(\rho^t, \rho_{t+1})) - u(e_{t+1}^o)\right),$$

where $u(\cdot)$ is the per-period utility function, common to both the young and the old, and $\beta \in (0, 1]$ is the generational discount factor. We assume that the per-period utility function is logarithmic, $u(\cdot) = \log(\cdot)$. Given logarithmic utility, the preferences of an agent can be expressed in terms of consumption and endowment shares. In particular, since $e_t^y = s_t e_t$ and $C(\rho^t) = c(\rho^t)e_t$, it follows that $u(C(\rho^t)) - u(e_t^y) = \log(c(\rho^t)) - \log(s_t)$ and that $U(\{C\};\rho^t) = U(\{c\};\rho^t)$ where

$$U\left(\{c\};\rho^t\right) := \log(c(\rho^t)) - \log(s_t) + \beta \sum\nolimits_{\rho_{t+1}} \varpi(\rho_t, \rho_{t+1}) \left(\log(1 - c(\rho^t, \rho_{t+1})) - \log(1 - s_{t+1})\right).$$

We call the history-contingent stream of consumption shares $\{c\} = \{c(\rho^t): t \geq 0, \rho^t \in \mathcal{P}^t\}$ an *intergenerational insurance rule* since it determines how consumption is allocated between the young and the old for any history ρ^t. In the absence of a storage technology and because the young are born after uncertainty is resolved, the only possibility for intergenerational insurance is through transfers between the young and the old. We assume that there is a benevolent social planner who chooses an intergenerational insurance rule of history-contingent transfers to maximize a discounted sum of the expected utilities of all generations. Let the planner's expected discounted utility gain over autarky, conditional on the history ρ^t, be

$$V\left(\{c\};\rho^t\right) := \frac{\beta}{\delta}\left(\log(1 - c(\rho^t)) - \log(1 - s_t)\right) + \mathbb{E}_t\left[\sum\nolimits_{j=t}^{\infty} \delta^{t-j} U\left(\{c\};\rho^j\right)\right]$$

where $\mathbb{E}_t$ is the expectation over future histories at time t. The discount factor of the planner is $\delta \in (0,1)$ and the weight on the utility of the initial old is β/δ.[4] In seeking to maximize the discounted sum of expected lifetime utilities the planner must respect the constraint that transfers are voluntary.[5] That is, the planner must respect the constraint that neither the old nor the young would be better off in autarky than adhering to the specified transfers for any history of shocks. For the old, this means they will not make a positive transfer to the young because there is no future benefit to offset such a transfer. Hence, the consumption of the young cannot exceed their endowment, or equivalently,

$$c(\rho^t) \leq s_t \quad \text{for all } t \geq 0 \text{ and } \rho^t \in \mathcal{P}^t. \tag{1}$$

The analogous participation constraint for the young requires that the conditional transfers promised for their old age sufficiently compensate for the transfer made when young so that they are no worse off than reneging on the transfer today and receiving the corresponding autarkic

[4]The assumption of geometric discounting for the planner is common (see, for example, Farhi and Werning, 2007). Using a weight of β/δ for the initial old preserves the same relative weights on the young and the old, including the initial old, in every period.

[5]The assumption that the transfer is voluntary can be interpreted as requiring that the intergenerational insurance rule is supported by each generation if put to a vote.

lifetime utility. That is,

$$U\left(\{c\};\rho^t\right) \geq 0 \quad \text{for all } t \geq 0 \text{ and } \rho^t \in \mathcal{P}^t. \tag{2}$$

For expositional simplicity, let the initial state ρ_0 be given.[6] Hence, at $t = 0$, the planner chooses $\{c\}$ to maximize:

$$V\left(\{c\};\rho_0\right), \tag{3}$$

subject to the constraint set $\Lambda := \{\{c\} \mid (1) \text{ and } (2)\}$. Since utility is strictly concave and the constraints in (2) are linear in utility, the planner's objective in equation (3) is concave and the constraint set Λ is convex and compact.

Definition 1. *An Intergenerational Insurance rule is sustainable if the history-dependent sequence* $\{c\} \in \Lambda$.

Definition 2. *A Sustainable Intergenerational Insurance rule is optimal if it maximizes the objective in equation* (3) *subject to the constraint that the initial old receive a utility from their consumption share of at least* $\bar{\omega}_0$*:*

$$\log(1 - c(\rho_0)) \geq \bar{\omega}_0. \tag{4}$$

We introduce constraint (4) with an exogenous initial target utility of $\bar{\omega}_0$ because it is useful when considering the evolution of the optimal sustainable intergenerational insurance rule in Section 4.[7] However, we will return to the case where the initial $\bar{\omega}_0$ is chosen by the planner.

Since $U(\{C\};\rho^t) = U(\{c\};\rho^t)$ and utility is logarithmic, the objectives and constraints are equivalent whether consumption is expressed in levels or shares. That is, the economy with stochastic growth is equivalent to an economy with a constant endowment and consumption expressed as shares of the aggregate endowment. The growth rate of the consumption levels is simply the growth rate of the consumption shares multiplied by the growth rate of the aggregate endowment.

Remark 1. *For preferences that exhibit constant absolute risk aversion, this property is well-known to hold in models of idiosyncratic and aggregate risk with infinitely-lived agents (see, for example, Alvarez and Jermann, 2001, Krueger and Lustig, 2010). An analogous extension can be shown to hold here by defining growth-adjusted transition probabilities and discount factors*

[6]The analysis is easily generalized to any given initial distribution $\varpi(\rho_0)$.

[7]The initial target utility may also depend on the initial state. Varying $\bar{\omega}_0$ traces out the Pareto frontiers that trade-off the utility of the old against the planner's valuation of the expected discounted utility of all future generations.

to satisfy:

$$\hat{\varpi}(\rho_t, \rho_{t+1}) := \frac{\varpi(\rho_t, \rho_{t+1})(\gamma_{t+1})^{1-\alpha}}{\sum_{\rho_{t+1}} \varpi(\rho_t, \rho_{t+1})(\gamma_{t+1})^{1-\alpha}} \text{ and } \frac{\hat{\beta}(\rho_t)}{\beta} = \frac{\hat{\delta}(\rho_t)}{\delta} := \sum_{\rho_{t+1}} \varpi(\rho_t, \rho_{t+1})(\gamma_{t+1})^{1-\alpha},$$

where α is the coefficient of relative risk aversion.[8]

In what follows, we make the simplifying assumption that the shocks to endowment shares and growth rates are independent of each other and are identically and independently distributed (hereafter, i.i.d.).

Assumption 1. *(i) The state ρ is i.i.d. with the probability given by $\varpi(\rho)$. (ii) The endowment share and the growth rate are independently distributed, that is, $\varpi(\rho) = \pi(s)\varsigma(\gamma)$ where $\pi(s)$ and $\varsigma(\gamma)$ are the marginal distributions for the endowment shares and the growth rates respectively.*

By the first part of Assumption 1, the economy is stationary. We make this assumption to emphasize that the history dependence we derive below follows from the participation constraints rather than from any feature of the economic environment itself.[9] Since the terms $U(\{c\}; \rho^t)$ and $V(\{c\}; \rho^t)$ depend on the growth rates γ_t and γ_{t+1} only via the transition function $\varpi(\rho_t, \rho_{t+1})$, it follows that the consumption shares in any optimal sustainable intergenerational insurance rule depend only on the history of endowment shares s^t and we have the following proposition.

Proposition 1. *Under Assumption 1, the consumption shares in any optimal sustainable intergenerational insurance rule depend only on the history s^t and are independent of the history of growth shocks γ^t.*

A similar result is well known from models with infinitely-lived agents (see, again, Alvarez and Jermann, 2001, Krueger and Lustig, 2010).[10] We will consider the asset pricing implications and contrast them to those from infinitely-lived models in Section 7.

Preliminaries. Since there are $I \geq 2$ states for the endowment share, order states such that $s(i) < s(i+1)$ for $i = 1, \ldots, I-1$. That is, a higher state corresponds to a larger endowment share for the young. For convenience, we will refer to states $1, 2, \ldots, I$ corresponding to the shares $s(1), s(2), \ldots, s(I)$ and to simplify notation will often express variables as a function of i rather than s.

[8] Assuming $\alpha \geq 1$ is sufficient for optimal consumption to be strictly positive.

[9] The assumption of i.i.d. shocks is common in OLG models where a generation may cover 20-30 years.

[10] Under Assumption 1 and preferences exhibiting constant relative risk aversion, the discount factors defined in Remark 1 satisfy $\hat{\beta}/\beta = \hat{\delta}/\delta = \sum_\gamma \varsigma(\gamma)\gamma^{1-\alpha}$. If $\alpha \neq 1$, then the planner's objective is finite provided $\delta \sum_\gamma \varsigma(\gamma)\gamma^{1-\alpha} < 1$.

Under Assumption 1, the existence of a non-autarkic sustainable allocation can be addressed by considering small stationary transfers that depend only on the current endowment state. Denote the intertemporal marginal rate of substitution between the consumption share when young in state s and the consumption share when old in state r next period, evaluated at autarky, by $\hat{m}(s,r) := \beta s/(1-r)$ and let $\hat{q}(s,r) := \pi(r)\hat{m}(s,r)$. The terms $\hat{m}(s,r)$ and $\hat{q}(s,r)$ correspond to the stochastic discount factor and the state prices in an equilibrium model. Denote the $I \times I$ matrix of terms $\hat{q}(s,r)$ by $\hat{Q}$. A non-autarkic sustainable allocation exhausting the aggregate endowment and satisfying the participation constraints in (1) and (2) exists whenever the Perron root of $\hat{Q}$ is greater than one (see, for example, Aiyagari and Peled, 1991, Chattopadhyay and Gottardi, 1999). In this case, there is a vector of strictly positive stationary transfers that improve the lifetime utility of the young in each state. Since the endowment states are independent, the matrix $\hat{Q}$ has rank one and the Perron root is its trace. We assume that the trace of $\hat{Q}$ is larger than the harmonic mean of the growth factors, $\bar{\gamma} := (\sum_{\gamma} \varsigma(\gamma)\gamma^{-1})^{-1}$.

Assumption 2. $\beta \sum_{i=1}^{I} \pi(i) \frac{s(i)}{1-s(i)} > \bar{\gamma}$.

If there is just one state with the young receiving a share s of the aggregate endowment and no growth, then Assumption 2 reduces to the standard Samuelson condition: $s > 1/(1+\beta)$. In this case, it is well known that there are Pareto-improving transfers from the young to the old.[11] Assumption 2 is the generalisation to the stochastic case and a natural assumption given that our focus is on transfers to the old.[12] Given Assumption 2, it follows that the constraint set Λ is non-empty.

Proposition 2. *Under Assumption 2, there exists a non-autarkic and stationary Sustainable Intergenerational Insurance rule.*

Furthermore, we assume:

Assumption 3. $s(1) \leq \delta/(\beta+\delta)$.

Assumption 3 provides a simple sufficient condition for the strong convergence result of Section 5. Since $\delta < 1$, Assumption 3 implies that $s(1) < 1/(1+\beta)$. That is, in the absence of growth the state-wise Samuelson condition does not hold in every state, showing that our results do not depend on this property. In the terminology of Gale (1973), the economy can be viewed as a mix of Samuelson and classic cases.

[11] If the young transfer one unit to the old, the marginal cost is $1/s$ whereas the marginal benefit to the old is $\beta/(1-s)$. The marginal cost is less than the marginal benefit when $s > 1/(1+\beta)$.

[12] A simple sufficient condition for Assumption 2 to be satisfied is that the Frobenius lower bound, given by the minimum row sum of $\hat{Q}$, is greater than $\bar{\gamma}$. A row sum greater than $\bar{\gamma}$ implies that in autarky the young would, if they could, save for their old age in each endowment state, even at a zero net rate of interest.

3 Two Benchmarks

Before turning to the characterization of the optimal sustainable intergenerational insurance, it is helpful to consider two benchmark cases that serve to illustrate the inefficiencies generated by the presence of limited enforcement and uncertainty. The first benchmark ignores the participation constraints of the young but not the participation constraints of the old. The second benchmark considers an economy without risk but requires that the planner respects the participation constraints of both the young and the old.

First Best. Suppose the planner ignores the participation constraints of the young and let $\Lambda^* := \{\{c\} \mid (1)\}$ denote the set of transfers without the constraints in (2).[13]

Definition 3. *An Intergenerational Insurance $\{c\} \in \Lambda^*$ is first best if it maximizes the objective function* (3) *subject to constraint* (4).

It is easy to verify that at the first-best optimum:

$$c^*(s^t) = \min\left\{\frac{\delta}{\beta+\delta}, s_t\right\} \quad \text{for all } t > 0 \text{ and } s^t \in \mathcal{S}^t. \tag{5}$$

Condition (5) shows that the consumption shares of the young are kept constant unless doing so would involve a transfer from the old to the young, in which case the consumption share is the autarky value.[14] That is, at the first-best, the consumption share is independent of the history s^{t-1} and depends only on the current endowment share s_t when the non-negativity constraint on the transfer binds. Under Assumption 3, there is always one state in which the participation constraint of the old holds with equality.

It can be seen from condition (5) that for states in which transfers are positive, the first-best consumption share of the young is independent of s. It is decreasing in β since a higher β puts more weight on the utility of the old who receive the transfer, and it is increasing in δ since a higher δ puts more weight on the utility of the young who make the transfer.

Let $\omega_{\min}(s) := \log(1-s)$ be the utility of the old at autarky and $\omega^* := \log(\beta/(\beta+\delta))$ be the utility of the old when the consumption share of the young is constant. Then, $\omega^*(s) := \max\{\omega_{\min}(s), \omega^*\}$ is the utility of the old at the first-best solution when the endowment share of the young is s. Since s_0 is the endowment share of the young at the initial date, it follows

[13] Hereafter, the asterisk designates the first-best outcome. Note that the first best could be defined by assuming that the planner ignores the participation constraints of both the young and the old. The reason for presenting the first best as we do is to show that this allocation is stationary. Hence, any history dependence of the optimal sustainable intergenerational insurance rule derives from the imposition of the participation constraints of the young.

[14] Condition (5) is a special case of the familiar Arrow-Borch condition for optimal risk sharing modified to account for the constraint that transfers are only from the young to the old.

from Definition 2 that constraint (4) does not bind when $\bar{\omega}_0 \leq \omega^*(s_0)$. In this case, the first-best consumption at $t = 0$ is $c^*(s_0)$, determined by condition (5) as in every other time $t > 0$. On the other hand, for $\bar{\omega}_0 > \omega^*(s_0)$, constraint (4) binds and $c^*(s_0) = 1 - \exp(\bar{\omega}_0)$.In this case, the initial transfer to the old is correspondingly higher than implied by condition (5).

Denote the per-period payoff to the planner with the first-best allocation by $v^*(s) = \log(c^*(s)) + (\beta/\delta)\log(1 - c^*(s))$ and the expected discounted payoff to the planner by $V^*(s_0, \omega)$ when the initial endowment share is s_0 and the initial utility of the old is ω. The maximum utility the old can get occurs if they consume all of the endowment, so that $\omega_{\max} = \log(1) = 0$. Let $\Omega(s_0) = [\omega_{\min}(s_0), 0]$ be the set of possible utilities for the old at the initial state, $\bar{v}^* := \sum_s \pi(s)v^*(s)$ be the planner's expected per-period payoff at the first-best solution and $\bar{V}^* := \bar{v}^*/(1-\delta)$ be the corresponding continuation payoff. The first-best outcome is summarized in the following proposition.[15]

Proposition 3. *(i) The consumption share $c^*(s^t)$ is stationary and satisfies condition* (5) *for $t > 0$. For $t = 0$, $c^*(s_0)$ satisfies condition* (5) *for $\omega \leq \omega^*(s_0)$ and $c^*(s_0) = 1 - \exp(\omega)$ for $\omega > \omega^*(s_0)$. (ii) The value function $V^*(s_0, \cdot)\colon \Omega(s_0) \to \mathbb{R}$ has $V^*(s_0, \omega) = v^*(s_0) + \delta\bar{V}^*$ for $\omega \leq \omega^*(s_0)$ and $V^*(s_0, \omega) = (\beta/\delta)\omega + \log(1 - \exp(\omega)) + \delta\bar{V}^*$ for $\omega > \omega^*(s_0)$, where the derivative $V^*_\omega(s_0, \omega^*(s_0)) = \min\{0, (\beta/\delta) - ((1 - s_0)/s_0)\}$ with $\lim_{\omega\to 0} V^*_\omega(s_0, \omega) = -\infty$.*

The value function $V^*(s_0, \omega)$ is decreasing and concave in ω (strictly decreasing and strictly concave in ω for $\omega > \omega^*(s_0)$). The function "extends to the left" when the endowment share s_0 is higher.[16] If $\omega^*(s_0) > \omega_{\min}(s_0)$ (or equivalently, if $s_0 > \delta/(\beta + \delta)$), then $V^*(s_0, \omega)$ is independent of ω for $\omega \leq \omega^*(s_0)$. Hence, in the absence of constraint (4), the planner would choose $\omega(s_0) = \omega^*(s_0)$ because this gives the highest utility to the initial old while maximizing the payoff to the planner. In this case, the allocation given by condition (5) holds in every period. In contrast, when $\bar{\omega}_0 > \omega^*(s_0)$, the consumption share of the young is lower than implied by condition (5), but only in the initial period. There is immediate convergence to the stationary first-best distribution in one period.

Since the payoff to the planner depends both on s and ω, the stationary distribution is a pair $(s, \omega^*(s))$, the endowment share and the corresponding utility promised to the old. We note for future reference, that this stationary distribution has I values, one for each endowment state, with the probability of each pair given by $\pi(s)$.

Deterministic Economy. We now consider a deterministic economy with a constant growth rate γ and endowment share s. Unlike the previous benchmark, we assume that the plan-

[15] The proof of Proposition 3 is omitted because it follows from standard arguments. Nonetheless, the properties of the function $V^*(s_0, \omega)$ are mirrored in Proposition 4 and Lemma 1, given below, which do respect the participation constraints of the young.

[16] That is, for $s > r$ where $\omega_{\min}(s) < \omega_{\min}(r)$, $V^*(s, \omega) = V^*(r, \omega)$ for $\omega \in \Omega(r)$.

ner respects the participation constraint of the young as well as that of the old. Let $\hat{v} := \log(s) + \beta \log(1 - s)$ be the lifetime endowment utility. Assumption 2 together with the strict concavity of the utility function implies that there is a unique $c_{\min} < s$, which is the lowest *stationary* consumption share of the young that satisfies the participation constraint with equality. The corresponding maximum utility of the old is $\omega_{\max} := \log(1 - c_{\min})$.[17] Analogously to condition (5), the first-best consumption share is $c^* = \delta/(\beta + \delta)$ and the corresponding utility of the old is $\omega^* := \log(\beta/(\beta + \delta))$. If δ is above a critical value, then $c^* > c_{\min}$ (or equivalently, $\omega^* < \omega_{\max}$) and the first-best consumption share is sustainable. Otherwise, the first-best consumption share is not sustainable.

Denote the consumption share of the young at time t by c_t and the corresponding utility of the old by $\omega_t = \log(1 - c_t)$. Consider the maximization problem in (3) with the participation constraints of the young given by $\log(c_t) + \beta \log(1 - c_{t+1}) \geq \hat{v}$. For $\bar{\omega}_0 \leq \omega^*$, constraint (4) does not bind and it is optimal to set $c_t = \max\{c^*, c_{\min}\}$ (or equivalently, $\omega_t = \min\{\omega^*, \omega_{\max}\}$) for all $t \geq 0$. On the other hand, consider the case where $\omega^* < \omega_{\max}$ and $\bar{\omega}_0 > \omega^*$. Then, at $t = 0$, c_0 must satisfy $\log(1 - c_0) \geq \bar{\omega}_0$, which requires that $c_0 < c^*$. Clearly, it is desirable to set c_0 such that $\log(1 - c_0) = \bar{\omega}_0$ and $c_1 = c^*$. However, setting $c_1 = c^*$ may violate the participation constraint of the young. In this case, c_1 has to be chosen to satisfy $\log(c_0) + \beta \log(1 - c_1) = \hat{v}$, which implies that $c_1 < c^*$. Repeating this argument for $t > 1$ shows that given c_t, the consumption share of the young at time $t + 1$ either satisfies $\log(c_t) + \beta \log(1 - c_{t+1}) = \hat{v}$ or $c_{t+1} = c^*$ if $\log(c_t) + \beta \log(1 - c^*) \geq \hat{v}$. Intuitively, if the consumption of the young is low (or equivalently, if the utility of the old is large), then the planner would like to raise the consumption of the young to c^* (or equivalently, reduce ω to ω^*) as fast as possible to improve welfare. But if the consumption of the next-period young is raised too much, then the lifetime utility of the current young falls and their participation constraint is violated. That is, in the presence of limited enforcement the consumption of the young has to be raised gradually. It is useful to express this rule in terms of a policy function $g(\omega)$ for the promised utility next period, where

$$g(\omega) := \begin{cases} \omega^* & \text{for } \omega \in [\omega_{\min}, \omega^c], \\ \frac{1}{\beta}\left(\hat{v} - \log\left(1 - \exp(\omega)\right)\right) & \text{for } \omega \in (\omega^c, \omega_{\max}], \end{cases} \tag{6}$$

with $\omega_{\min} = \log(1 - s)$ and $\omega^c := \log(1 - \exp(\hat{v} - \beta\omega^*))$. It follows from the strict concavity of the utility function that $\omega^c > \omega^*$. The function $g(\omega)$ is increasing and convex in ω as illustrated in Figure 1. The dynamic evolution of ω_t is straightforwardly derived from $g(\omega)$: for

[17] The maximum utility of the old can be found by solving $\log(1 - \exp(\omega_{\max})) + \beta\omega_{\max} = \hat{v}$. Equivalently, the minimum consumption is found by solving $\log(c_{\min}) + \beta \log(1 - c_{\min}) = \hat{v}$.

$\omega_t \in [\omega_{\min}, \omega^c]$, $\omega_{t+1} = \omega^*$ for all t; for $\omega_t \in (\omega^c, \omega_{\max}]$, ω_{t+1} declines monotonically. Since $\omega^c > \omega^*$, the process for ω_t converges to ω^*, attaining its long-run value in finite time.

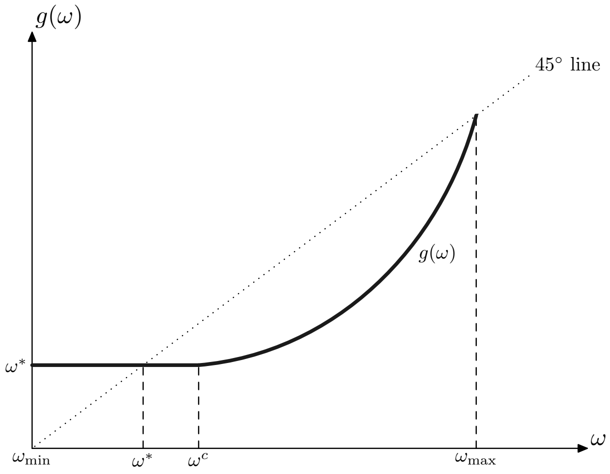

Figure 1: Policy Function in the Deterministic Case with $\omega_{\max} > \omega^*$.

Note: The solid line is the deterministic policy function $g(\omega)$. For any initial $\omega \in [\omega_{\min}, \omega_{\max})$, ω_t converges to ω^*.

Denote the per-period payoff to the planner with the first-best allocation in the absence of uncertainty by $v^* := \log(\delta/(\beta + \delta)) + (\beta/\delta)\omega^*$ and the expected discounted payoff to the planner for $\omega \in \Omega := [\omega_{\min}, \omega_{\max}]$ by $V(\omega)$. The optimal solution for the deterministic case with sustainable ω^* is summarized in the following proposition.

Proposition 4. *(i) If $\omega \in [\omega_{\min}, \omega^*]$, then the consumption share $c_t = \delta/(\beta + \delta)$ for $t \geq 0$. (ii) If $\omega \in (\omega^*, \omega_{\max}]$, then ω_{t+1} satisfies equation* (6). *There exists a finite T such that ω_t is monotonically decreasing for $t < T$ and $\omega_t = \omega^*$ for $t \geq T$. Likewise, c_t is monotonically increasing for $t < T$ and $c_t = c^*$ for $t \geq T$. (iii) The value function $V\colon \Omega \to \mathbb{R}$ is equal to $V(\omega) = v^*/(1 - \delta)$ for $\omega \in [\omega_{\min}, \omega^*]$ and is strictly decreasing and strictly concave for $\omega \in (\omega^*, \omega_{\max}]$ with* $\lim_{\omega \to \omega_{\max}} V_\omega(\omega) = -\infty$.

The optimal solution is either stationary or converges monotonically to a stationary point within finite time with $c_T = c^*$ for T large enough. Hence, the long-run distribution of ω is degenerate and for the case where $c^* > c_{\min}$, it has a single mass point at $\{\omega^*\}$.

In the following sections, we show that when the first-best allocation violates a participation constraint of the young, and there is endowment risk, then there is history dependence in the long run and the ergodic set of utilities has more than I values. The benchmarks highlight that both limited enforcement of transfers and risk are necessary for this result.

4 Optimal Sustainable Intergenerational Insurance

In this section, we characterize the optimal intergenerational insurance rule under uncertainty when the planner respects the participation constraints of both the young and the old. Recall that the shocks to the growth rates and the endowment shares are i.i.d. (Assumption 1) and that the optimal sustainable consumption shares depend only on the history of endowment share s^t (Proposition 1). We rule out the case in which the first-best outcome is sustainable and assume that the first-best allocation violates the participation constraint of the young in at least one state. Since the lifetime endowment utility of an agent is increasing in s, we assume that:

Assumption 4. $\log(c^*(I)) + \beta \sum_r \pi(r) \log(1 - c^*(r)) < \log(s(I)) + \beta \sum_r \pi(r) \log(1 - r)$.

We reformulate the optimization problem described in Definition 2 recursively using the utility ω promised to the old as a state variable. Let ω_r denote the state-contingent utility promised to the current young for their old age when the endowment share of the young next period is r. Then, the planner's optimization problem is:

$$V(s, \omega) = \max_{\{c, (\omega_r)_{r \in \mathcal{I}}\} \in \Phi(s, \omega)} \frac{\beta}{\delta} \log(1 - c) + \log(c) + \delta \sum_r \pi(r) V(r, \omega_r), \tag{P1}$$

where $\Phi(s, \omega)$ is the constraint set given by the following inequalities:

$$\log(1 - c) \geq \omega, \tag{7}$$

$$c \leq s, \tag{8}$$

$$\omega_r \leq \omega_{\max}(r) \quad \text{for each } r \in \mathcal{I}, \tag{9}$$

$$\omega_r \geq \omega_{\min}(r) \quad \text{for each } r \in \mathcal{I}, \tag{10}$$

$$\log(c) + \beta \sum_r \pi(r) \omega_r \geq \log(s) + \beta \sum_r \pi(r) \log(1 - r). \tag{11}$$

The recursive formulation is similar to the promised-utility approach used in models with infinitely-lived agents (see, for example, Green, 1987, Spear and Srivastava, 1987, Thomas and Worrall, 1988, Atkeson and Lucas Jr., 1992). At each period, the planner chooses the consumption share of the young, c, and the state-contingent promise of utility, ω_r. The state variable ω embodies information about the history of shocks. Constraint (7) is the promise-keeping constraint which requires that the current old should receive at least what they were previously promised. It is analogous to constraint (4) but it is now required to hold in every period. Constraint (8) is the participation constraint for the old which stipulates that the old do not transfer to the young. Constraints (9) and (10) require that the promise is feasible: $\omega_r \in \Omega(r) := [\omega_{\min}(r), \omega_{\max}(r)]$. Finally, constraint (11) requires that the consumption share of the young and the promises made to them for their old age at least matches their expected lifetime utility from autarky.

It is easy to check that the constraint set $\Phi(s, \omega)$ is convex and compact. Denote the state vector by $x := (s, \omega)$ and let $f(x)$ and $g_r(x)$ for $r \in \mathcal{I}$ be the optimum consumption share of the young and the state-contingent promise of utility of the old next period. The compactness of the constraint set guarantees the existence of the optimal policies and the strict concavity of the utility function guarantees uniqueness. The optimal allocation is solved recursively. Starting at date $t = 0$ with a given state s_0 and given $\omega_0 \in \Omega(s_0)$, solve the optimization problem P1 to obtain the policy functions $f(s_0, \omega_0)$ and $g_r(s_0, \omega_0)$ for $r \in \mathcal{I}$. For the second period, resolve the maximization problem using the endowment share realized at date 1, say $\hat{r}$, with the utility promise from the first period, $g_{\hat{r}}(s_0, \omega_0)$, in equation (7). The process is then repeated for subsequent periods.

The function $V(s, \omega)$ cannot be found by standard contraction mapping arguments starting from an arbitrary value function because the value function associated with the autarkic allocation also satisfies the functional equation of problem P1. Nevertheless, a similar iterative approach can be used to solve for the value function, starting from the first-best value functions $V^*(s, \omega)$ derived in Proposition 3. Following the arguments of Thomas and Worrall (1994), the limit of this iterative mapping is the optimal value function $V(s, \omega)$.[18] Proposition 3 established that the first-best value function is non-increasing, differentiable and concave in ω, and the limit value function inherits these properties.

Lemma 1. *(i) The value function $V(s, \cdot)\colon \Omega(s) \to \mathbb{R}$ is non-increasing, concave and continuously differentiable in ω, with $\omega_{\min}(s) < \omega_{\max}(s)$. (ii) For each $s \in \mathcal{I}$, there exists an $\omega^0(s) \in [\omega_{\min}(s), \omega^*(s)]$ such that $V(s, \omega)$ is strictly decreasing and strictly concave for $\omega > \omega^0(s)$. If $\omega^*(s) > \omega_{\min}(s)$, then $\omega^0(s) < \omega^*(s)$ for some state s and $\omega^0(s) > \omega_{\min}(s)$ for some (possibly different) state. For $\omega \in [\omega_{\min}(s), \omega^0(s)]$, $V_\omega(s, \omega) = 0$. If $\omega^*(s) = \omega_{\min}(s)$, then $\omega^0(s) = \omega^*(s)$ and $V_\omega(s, \omega^0(s)) \leq (\beta/\delta) - ((1-s)/s) \leq 0$. In either case, $\lim_{\omega \to \omega_{\max}(s)} V_\omega(s, \omega) = -(\beta/\delta)\lambda_{\max}(s)$, where $\lambda_{\max}(s) \in \mathbb{R}_+ \cup \{\infty\}$. (iii) The upper bounds satisfy $\omega_{\max}(s(i)) < \omega_{\max}(s(i-1)) < 0$. Similarly, $\omega^0(s(i)) \leq \omega^0(s(i-1))$ with strict inequality for at least one $i = 2, \ldots, I$.*

The strict concavity of the objective function and the convexity of the constraint set guarantee the concavity of $V(s, \omega)$ in ω with $\omega^0(s) = \sup\{\omega \mid V_\omega(s, \omega) = 0\}$ if $V_\omega(s, \omega_{\min}(s)) = 0$ and $\omega^0(s) = \omega_{\min}(s)$ otherwise. Since the old will not transfer to the young voluntarily, $\omega_{\min}(s) = \log(1-s)$, the autarkic utility of the old, which is decreasing in s. The upper endpoints

[18] We use a similar procedure to compute the optimal value function for the numerical examples considered in Section 9.

$\omega_{\max}(s)$ are determined by the system of equations $\log(1-\exp(\omega_{\max}(s)))+\beta\sum_r \pi(r)\omega_{\max}(r) = \log(s)+\beta\sum_r \pi(r)\log(1-r)$. It can be checked that there is a unique non-trivial solution with $\omega_{\max}(s)$ decreasing with s and $\omega_{\min}(s) < \omega_{\max}(s) < 0$. Likewise, $\omega^0(s)$ is decreasing in s. Differentiability of $V(s,\omega)$ with respect to ω follows because the constraint set satisfies a linear independence constraint qualification when $\omega \in [\omega_{\min}(s), \omega_{\max}(s))$. The left-hand derivative of $V(s,\omega)$ with respect to ω evaluated at $\omega_{\max}(s)$ is finite if $\omega_{\max}(s)$ is part of the ergodic set and infinite otherwise.

Remark 2. *Recall that $\bar{\omega}_0$ is the exogenous target utility given in constraint (4). Given the definition of $\omega^0(s)$, the planner chooses the initial utility of the old such that $\omega_0 = \max\{\omega^0(s_0), \bar{\omega}_0\}$. If the planner is not subject to constraint (4) and can freely choose the initial utility, then the planner sets $\omega_0 = \omega^0(s_0)$. Note that each $\omega^0(s)$ is an optimal choice and depends on all of the primitives of the model.*

Remark 3. *The optimal sustainable intergenerational insurance is not renegotiation-proof because in the case of default, it would be possible to offer the promised utility $\omega^0(r)$ instead of $\omega_{\min}(r)$ without diminishing the planner's payoff. A renegotiation-proof outcome can then be derived by replacing constraint (11) by $\log(c)+\beta\sum_r \pi(r)\omega_r \geq \log(s)+\beta\sum_r \pi(r)\omega^0(r)$. Since $\omega^0(r)$ is determined as part of the solution and appears in the constraint, a fixed-point argument similar to that used by Thomas and Worrall (1994) is required to find the solution. Although imposing this tighter constraint restricts risk sharing, the structure of the constrained optimization problem is not affected and we expect that the qualitative properties of the optimal solution are substantially unchanged.*

Optimal Policy Functions. We now turn to the properties of the policy functions $f(x)$ and $g_r(x)$. Given the differentiability of the value function, the first-order conditions for the programming problem P1 are:

$$f(x) = \min\left\{\frac{\delta(1+\mu(x))}{\beta(1+\lambda(x))+\delta(1+\mu(x))}, s\right\} \tag{12}$$

$$V_\omega(r, g_r(x)) = -\frac{\beta}{\delta}\left(\mu(x)-\xi_r(x)+\eta_r(x)\right) \quad \text{for each } r \in \mathcal{I}, \tag{13}$$

where $(\beta/\delta)\lambda(x)$ is the multiplier associated with the promise-keeping constraint (7), $\beta\pi(r)\xi_r(x)$ are the multipliers associated with the upper bound on the promised utility (9), $\beta\pi(r)\eta_r(x)$ are the multipliers associated with the lower bound on the promised utility (10), and $\mu(x)$ is the multiplier associated with the participation constraints of the young (11). Given the concavity of the programming problem, conditions (12) and (13) are both necessary and sufficient. There is also an envelope condition:

$$V_\omega(x) = -\frac{\beta}{\delta}\lambda(x). \tag{14}$$

Taken together, equations (13) and (14) imply the following updating property:

$$\lambda(x') = \mu(x) - \xi_r(x) + \eta_r(x), \tag{15}$$

where $x' = (r, g_r(x))$ is the next-period state variable. Equation (15) is easy to interpret. For simplicity, suppose that the boundary constraints on the promised utility do not bind, that is, $\xi_r(x) = \eta_r(x) = 0$. From equation (13), it follows that $\delta(1 + \mu(x))$ is the relative weight placed on the utility of the young and $\beta(1 + \lambda(x))$ is the relative weight placed on the utility of the old. The updating property in equation (15) shows that the relative weight placed on the utility of the old corresponds to the tightness of the participation constraint they faced when they were young.

The following two Lemmas describe the properties of the policy functions.[19]

Lemma 2. *(i) The policy function $g_r(s, \cdot)\colon \Omega(s) \to [\omega^0(r), \omega_{\max}(r)]$ is continuous and increasing in ω and strictly increasing for $g_r(s, \omega) \in (\omega^0(r), \omega_{\max}(r))$. (ii) For each $r \in \mathcal{I}$ and $\omega \in (\omega_{\min}(s(i-1)), \omega_{\max}(s(i)))$, $g_r(s(i), \omega) \geq g_r(s(i-1), \omega)$ with strict inequality for at least one $i = 2, \ldots, I$. For each $s \in \mathcal{I}$, $g_{r(i)}(s, \omega) \leq g_{r(i-1)}(s, \omega)$ with strict inequality for at least one $i = 2, \ldots, I$. (iii) For endowment state 1, there is a critical value $\omega^c > \omega^0(1)$ such that $g_r(1, \omega) = \omega^0(r)$ for $\omega \in [\omega^0(1), \omega^c]$ and $r \in \mathcal{I}$. (iv) For each $s \in \mathcal{I}$, there is a unique fixed point $\omega^f(s) = \min\{\omega^*(s), \omega_{\max}(s)\}$ of the mapping $g_s(s, \omega)$ with $g_s(s, \omega) > \omega$ for $\omega < \omega^f(s)$ and $g_s(s, \omega) < \omega$ for $\omega > \omega^f(s)$. For endowment state I, $\omega^f(I) > \omega^0(I)$.*

Lemma 3. *(i) The policy function $f(s, \cdot)\colon \Omega(s) \to (0, s]$ where $f(s, \omega) = 1 - \exp(w)$ for $\omega \geq \omega^0(s)$ and $f(s, \omega) = 1 - \exp(\omega^0(s))$ for $\omega < \omega^0(s)$. (ii) $c^0(s) := f(s, \omega^0(s))$ where $c^0(s(i)) \geq c^0(s(i-1))$ with strict inequality for at least one $i = 2, \ldots, I$. (iii) At the fixed point $\omega^f(s)$, $f(s, \omega^f(s)) \leq c^*(s)$ with equality for $\omega^f(s) < \omega_{\max}(s)$.*

The main properties of Lemmas 2 and 3 follow straightforwardly from the objective to share risk subject to the participation constraints. The policy function $g_r(s, \omega)$ is increasing in ω (Lemma 2(i)), whereas $f(s, \omega)$ is decreasing in ω (Lemma 3(i)). A higher promise to the current old means a lower consumption share for the current young and, for endowment states in which the participation constraint binds, this requires a higher future promise of utility for their old age as compensation. The consumption share of the young depends only indirectly

[19]To avoid the clumsy terminology of non-decreasing or weakly increasing, we describe a function as increasing if it is weakly increasing and highlight cases where a function is strictly increasing.

on s when $\omega = \omega^0(s)$ or $\omega = \omega_{\max}(s)$ (Lemma 3(ii)), whereas $g_r(\omega, s)$ is increasing in s and decreasing in r (Lemma 2(ii)). The policy function $g_r(\omega, s)$ is increasing in s because a higher endowment share of the young today is associated with a larger risk-sharing transfer, which if the participation constraint is binding, has to be compensated by a higher promise for tomorrow. Likewise, the future promise is decreasing in r because a higher endowment share of the young tomorrow is associated with a higher consumption share when the participation constraint binds and hence, a lower consumption share of the old tomorrow. Since the optimum is non-trivial and different from the first best, there is at least one strict inequality in the relations of Lemma 2(ii), so that, $g_r(s(I), \omega) > g_r(s(1), \omega)$ and $g_{r(I)}(s, \omega) < g_{r(1)}(s, \omega)$.

Lemma 2(iii) shows that there is a range of ω above $\omega^0(1)$ such that the participation constraint of the young does not bind and hence, $g_r(1, \omega) = \omega^0(r)$ in this range. This is analogous to the deterministic case discussed in Section 3 where the policy function has an initial flat section (see, Figure 1). More generally, when the participation constraint of the young does not bind, it follows from equation (14) that $g_r(x) = \omega^0(r)$ and $x' = (r, \omega^0(r))$. In this case, we say that the promise is *reset*. It is reset to the value that gives the most to the current old while maximizing the payoff to the planner. Lemma 2(iii) shows that resetting, in particular, occurs in state 1 for any $\omega \in [\omega^0(1), \omega^c]$.

Lemmas 2(iv) and Lemma 3(iii) describe what happens when the same endowment share repeats in successive periods. Suppose for simplicity that $\eta_s(x) = \xi_s(x) = 0$ and $f(x) > s$. From equations (13) and (14), $\mu(s, \omega^f(s)) = \lambda(s, \omega^f(s))$ where $\omega^f(s)$ is the fixed point of $g_s(s, \omega)$. Using equation (12), this implies that the consumption share is first best and hence, $\omega^f(s) = \omega^*(s)$. Furthermore, $g_s(s, \omega) > \omega$ for $\omega < \omega^f(s)$ and $g_s(s, \omega) < \omega$ for $\omega > \omega^f(s)$. That is, when the same endowment share repeats, the promise falls if the previous promise was above the first best and rises if the previous promise was below the first best. It follows that the policy function $g_s(s, \omega) > \omega$ cuts the 45° line once from above. To understand this, consider some $\omega > \omega^f(s)$ and suppose, to the contrary, that $g_s(s, \omega) \geq \omega$. In this case, equations (13) and (14) imply that $\mu(s, \omega^f(s)) > \lambda(s, \omega^f(s))$, which in turn implies $\omega < \omega^*(s) = \omega^f(s)$ from equation (12), a contradiction. A similar argument shows that $g_s(s, \omega) > \omega$ for $\omega < \omega^f(s)$.[20]

The implications of Lemmas 2 and 3 can be illustrated by considering a particular *sample path* of the consumption share generated for a given history of endowment shares $s^T = (s_0, s_1, \ldots, s_T)$. The sample path of the consumption share is constructed iteratively from the policy functions $f(s, \omega)$ and $g_r(s, \omega)$ starting with $x_0 = (s_0, \omega_0)$ as follows: $c_t = f^t(s^t, x_0) := f(s_t, g^t(s^t, x_0))$, where $g^t(s^t, x_0) := g_{s_t}(s_{t-1}, g^{t-1}(s^{t-1}, x_0))$ and $g^0(s_0, x_0) = \omega_0$.

[20] The argument can be extended to the case where the non-negativity and upper bound constraints bind and the complete proof of Lemma 2 is given in the Online Appendix.

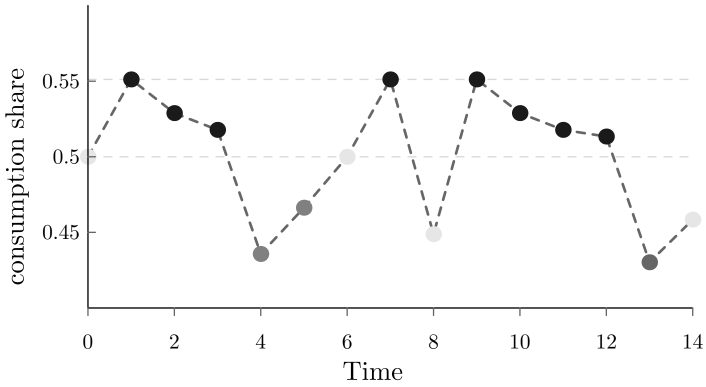

Figure 2: Sample Path of the Young Consumption Share.

Note: The illustration is for a case where $I = 3$ and $\beta = \delta$ (with first-best consumption share of $1/2$). The shade of the dots indicates the state s_t: light gray for $s_t = s(1)$, mid gray for $s_t = s(2)$ and dark gray for $s_t = s(3)$. The case illustrated has $s_0 = s(1)$ and $\omega_0 = \omega^0(1) = -\log(2)$.

Figure 2 depicts such a sample path in a three-state example and illustrates three important properties.[21] First, the path is history dependent. That is, the consumption share varies both with the current endowment state and the history of shocks. For example, the endowment share $s_t = s(3)$ occurs at both $t = 7$ and $t = 12$, but the consumption share is different at the two dates. When state 3 occurs, the participation constraint of the young binds and hence, a higher future utility must be promised to them to ensure that they are willing to share more of their current endowment. Subsequent realizations of state 3 exacerbate the situation because the young of the next generation must deliver on past promises as well, meaning that the consumption share of the young falls when state 3 repeats. This property is evident in Figure 2 where c_t falls when state 3 repeats ($t = 3, 4$ and $t = 10, 11, 12$). Secondly, the optimal sustainable consumption share fluctuates above and below the first-best level of $1/2$.[22] Thirdly, there are points in time at which the consumption share returns to the same value in the same state. For example, this happens at $t = 6$, which has the same state (state 1) and same consumption as at $t = 0$. In this case, there is *resetting*. The path of the consumption share is the same following resetting if the same sequence of endowment shares occurs. Note that the definition of the resetting points is not unique. For example, there is resetting also at $t = 1, 7, 9$, when state 3 occurs after state 1. Before resetting occurs, the effect of a shock persists. However, once resetting occurs, the history of shocks is forgotten and the subsequent sample path is identical when the same sequence of states occurs. That is, the sample paths between resettings are probabilistically

[21] The example has $\beta = \delta = 0.975$, $s(1) = 0.55$, $s(2) = 0.625$ and $s(3) = 0.8125$, with probabilities $\pi(1) = 0.6875$ and $\pi(2) = 0.0625$. In this case, the first-best is $c^*(s) = 0.5$ for each state.

[22] By Lemma 1(ii), $\omega^0(s) \leq \omega^*(s)$. By Assumption 3, $\omega^*(1) = \omega_{\min}(1)$. Hence, $\omega^0(1) = \omega^*(1)$. Since $g_1(s, \omega)$ is increasing in ω, the promise is above the first-best level (or equivalently, the consumption share is below the first-best level) in state 1. From Lemma 2(iii), $\omega^0(I) < \omega^*(I)$ and therefore, for low values of ω, the promise is below the first-best level (or equivalently, the consumption share is above the first-best level) in state I.

identical. This property is used in the next section to establish convergence to a unique invariant distribution.

5 Convergence to the Invariant Distribution

This section considers the long-run distribution of the pair $x = (s, \omega)$ and shows that there is a unique and countable ergodic set E with cardinality $|E| > I$ and strong convergence to the corresponding invariant distribution. Let $\Omega = \cup_{r\in\mathcal{I}}\Omega(r)$ and $\mathcal{X} = \mathcal{I} \times \Omega$. The future evolution of x is a Markov chain defined by the transition function $P(x, A \times B) := \Pr\{x_{t+1} \in A \times B \mid x_t = x\} = \sum_{r\in A} \pi(r)\mathbb{1}_B g_r(x)$ where $A \subseteq \mathcal{I}$, $B \subseteq \Omega$ and $\mathbb{1}_B g_r(x) = 1$ if $g_r(x) \in B$ and zero otherwise. The chain starts from $x_0 = (s_0, \omega_0)$ with an initial promise $\omega_0 = \max\{\omega^0(s_0), \bar{\omega}_0\}$.

The monotonicity and resetting properties of Lemma 2 imply that starting from any x_t, a sequence of k consecutive state 1s (where the endowment share is $s(1)$) leads to $x_{t+k} = (1, \omega^0(1))$ for a finite k. This is because $g_1(1, \omega) < \omega$, so that repetition of state 1 leads to a fall in ω and since $g_1(1, \omega) = \omega^0(1)$ for some $\omega > \omega^0(1)$, ω falls to $\omega^0(1)$ in finite time. In this case, we say that x is *reset* to $(1, \omega^0(1))$ at time $t + k$. Since the probability of the state 1 is $\pi(1) > 0$, the probability of a history of k consecutive state 1s is $\pi(1)^k > 0$. An immediate consequence is that Condition **M** of Stokey et al. (1989, page 348) is satisfied and hence, there is strong convergence in the uniform metric to a unique invariant probability measure $\phi(X)$ for $X \in \mathcal{X}$.[23]

Since there is a positive probability that x is reset to $(1, \omega^0(1))$ in finite time, the Markov chain for x is *regenerative* and $(1, \omega^0(1))$ is a regeneration point (see, for example, Foss et al., 2018). For simplicity, first suppose that the process starts at $x_0 = (1, \omega^0(1))$. Recall that $g^t(s^t, x_0) = g_{s_t}(s_{t-1}, g^{t-1}(s^{t-1}, x_0))$ where $g^0(1, x_0) = \omega^0(1)$. Let $r_x := \min\{k \geq 1 \mid (s, g^k((s^{k-1}, s), x_0)) = x\}$ denote the first time at which the process is equal to x starting from x_0. Then, r_{x_0} is the first regeneration time, that is, the first time after the initial period at which x_0 reoccurs. Any sample path of promises can be divided into different blocks with each block starting at a regeneration time. This can be seen in Figure 2 where the first regeneration time occurs at $t = 6$. The blocks between regeneration points are not identical but, by the strong Markov property, they are i.i.d. That is, at each regeneration time, the past shocks are forgotten and the future evolution of x is probabilistically identical. The regeneration times are also i.i.d. and the expected time to regeneration is $\varphi := \mathbb{E}_0[r_{x_0}]$, the same for any block. Moreover, the

[23]Condition **M** is satisfied because there is a $k \geq 1$ and an $\epsilon > 0$ such that the k-step transition function $P^k(x, \{(1, \omega^0(1))\}) > \epsilon$ for any $x \in \mathcal{X}$. In this case, $(1, \omega^0(1))$ is an atom of the Markov chain. Açikgöz (2018), Foss et al. (2018) and Zhu (2020) use similar arguments to establish strong convergence in the case of an Aiyagari precautionary savings model with heterogeneous agents.

expected time to regeneration φ is finite since all positive probability paths must have a sequence of endowment states that lead to $x_0 = (1, \omega^0(1))$ as described above.

Now consider a starting point $x_0 = (i, \omega^0(i))$ for some initial state $s_0 = s(i)$. Since $g_i(1, \omega^0(1)) = \omega^0(i)$ by Lemma 2(iii), a positive probability path leading back to x_0 is constructed by a sequence of consecutive state 1s, as outlined above, followed by state i. Since the transition from state 1 to state i occurs with positive probability, $(i, \omega^0(i))$ is a regeneration point and the blocks between these regeneration points are also probabilistically identical. As discussed in Remark 2, in the absence of constraint (4), the planner sets $\omega_0 = \omega^0(i)$ and the process starts in the ergodic set. If, on the other hand, constraint (4) must be respected and $\bar{\omega}_0 > \omega^0(i)$, then $x_0 = (i, \bar{\omega}_0)$ and the process may start outside of the ergodic set. In this case, there is still a positive probability path back to a resetting point $(i, \omega^0(i))$. The only difference is that the first block in the regenerative process is different from subsequent blocks (which all start from $(i, \omega^0(i))$). However, this does not change the convergence properties of the process.

Let $R_x := \Pr(r_x < \infty)$ be the probability of attaining the pair $x = (s, \omega)$ in finite time starting from x_0. If $R_x > 0$, then x is said to be *accessible* from x_0. Since $x_0 = (i, \omega^0(i))$ has a positive probability mass and the set of endowment states $\mathcal{I}$ is finite and time is discrete, the associated set $E := \{x \mid R_x > 0\}$ is countable. Moreover, the set E is an equivalence class because every $x \in E$ is accessible from x_0 and there is a path from every accessible x back to x_0. Therefore, E is an absorbing set, that is, $P(x, E) = 1$ for all $x \in E$, and since no proper subset of E has this property, it is *ergodic* (see, for example, Stokey et al., 1989, chapter 11). Let φ_x denote the *expected return time* to x where $\varphi_{x_0} \equiv \varphi$. With φ finite, it follows that $R_x = 1$ and φ_x is finite for all $x \in E$, that is, each $x \in E$ is positive recurrent.

Since the ergodic set E is countable, standard results on the convergence of positive recurrent Markov chains apply. To state these results, let P denote the transition matrix with elements $P(x, x') = \pi(r)\mathbb{1}_{\omega_r, g_r(x)}$ where $x = (s, \omega)$ and $x' = (r, g_r(x))$. Similarly, let $P^k(x, x')$ be the elements of the corresponding k-period transition matrix.

Proposition 5. *(i) There is pointwise convergence to a unique and non-degenerate invariant distribution $\phi = \phi P$ where for each $x \in E$, $\phi(x) = \lim_{k\to\infty} P^k(\cdot, x) = \varphi_x^{-1}$. (ii) The invariant distribution can be found iteratively using $\phi_{t+1}(x') = \sum_{x\in E} P(x, x')\phi_t(x)$. (iii) The cardinality $|E| > I$.*

Parts (i) and (ii) of Proposition 5 are standard and show convergence to a unique invariant distribution where the probability of each $x \in E$ is the inverse of the expected return time. The invariant distribution can be computed iteratively given knowledge of the policy functions. In particular, for $s_0 = s(i)$, the invariant distribution can be computed from an initial distribution

$\phi_0(x) = 1$ if $x = (i, \omega^0(i))$ and $\phi_0(x) = 0$ otherwise.[24] Part (iii) shows that the cardinality of the ergodic set is greater than I. That is, at the invariant distribution there are multiple promised utilities associated with particular states and hence, the history of endowment shocks affects the consumption allocation even in the long run. This result contrasts with the two benchmarks considered in Section 3. If transfers are enforced, or if there is no risk, then convergence is to an ergodic set with a cardinality that equals the cardinality of the set of the endowment states.

Since Lemma 2(i) and (ii) show that $g_r(s, \omega)$ is increasing in s and ω, $g_r(I, \omega^*(I))$ is the largest promise that can be reached in state r starting with $x_0 = (i, \omega^0(i))$. If $g_r(I, \omega^*(I)) < \omega_{\max}(r)$, then any $x = (r, \omega)$ with $\omega \in (g_r(I, \omega^*(I)), \omega_{\max}(r))$ is not accessible from x_0 and therefore, such an x is transitory and is not part of the ergodic set. In Section 9 we compute the ergodic set and the invariant distribution in examples with $g_r(I, \omega^*(I)) < \omega_{\max}(r)$.[25]

Remark 4. *All the results of this and the previous section apply when preferences exhibit constant relative risk aversion. They also apply for any concave utility function if there is a constant aggregate endowment with no growth. Most of the results also apply if the aggregate endowment is state dependent. In particular, Lemmas 2 and 3 and Proposition 5 hold with the exception that the policy functions cannot be ordered by the endowment share (see, Lancia et al., 2022, for details).*

6 Debt

In this section, we reinterpret the optimal transfer to the old as debt. Suppose that the planner issues one-period state-contingent bonds. Bonds trade at the corresponding state prices generating bond revenue for the planner. The planner uses the debt to finance the transfer to the old, balancing the budget from its bond revenue and taxing the young. Given the bond prices and taxes, the young buy the correct quantity of state-contingent bonds to finance their optimal old-age consumption. With this interpretation, it is possible to examine the dynamics of debt and the fiscal reaction function. In Section 7, we consider the asset pricing implications of the model and in Section 8, we address the question of debt valuation and sustainability studied by Bohn (1995) and others.

The Debt Policy Function. It is convenient to measure debt relative to the current endowment share of the young. Then, the optimal debt $d(x)$ satisfies $1 - s + sd(x) = 1 - f(x)$, where $f(x)$ is the optimal consumption share defined in Lemma 3. Using the properties of Lemmas 2

[24] The convergence results hold for any initial distribution $\phi_0(A)$ even if $A \not\subseteq E$ since eventually, once regeneration occurs, all subsequent promises belong to the ergodic set.

[25] The ergodic set and invariant distribution are difficult to characterize. In some cases, however, the invariant distribution is a transformation of a geometric distribution with a denumerable ergodic set, that is, $|E| = \aleph_0$.

and 3, both $d(x)$ and $sd(x)$ are increasing in s and ω.[26] Therefore, $d^0(s) := d(s, \omega^0(s)) \geq 0$ is the minimum debt at the optimal solution when the endowment share of the young is s. Debt $d \in \mathcal{D} = [d_{\min}, d_{\max}]$ where the minimum debt $d_{\min} := \min_r d^0(r)$ and the maximum debt $d_{\max}$ is determined as the non-trivial solution of $\log(1 - d_{\max}) + \beta \sum_r \pi(r)(\log(1 - r + r d_{\max}) - \log(1 - r)) = 0$. The properties of the *debt policy function* $b_r \colon \mathcal{D} \to \mathcal{D}$, which determines the optimal debt next period when the current debt is d and the endowment share of the young next period is r, are summarized in the following corollary to Lemmas 2 and 3.

Corollary 1. *(i) The debt policy function $b_r \colon \mathcal{D} \to \mathcal{D}$ is continuous in d with $b_r(d) = d^0(r)$ for $d \leq d^c$ and $b_r(d)$ strictly increasing for $d > d^c$. The debt threshold d^c satisfies $d^c = 1 - \exp(-\beta \sum_r \pi(r)(\log(1 - r + r d^0(r)) - \log(1 - r))) \in (d_{\min}, d_{\max})$ with $d_{\min} = 0$ and $d_{\max} < 1$. (ii) For $d \in \mathcal{D}$, $b_{r(i)}(d) \geq b_{r(i-1)}(d)$ with strict inequality for at least one $i = 2, \ldots, I$. (iii) For each $r \in \mathcal{I}$, there is a unique fixed point $d^f(r)$ of the mapping $b_r(d)$ where $d^f(r) = \min\{d^*(r), d_{\max}\}$, $d^*(r) = 1 - c^*(r)/r$ is the first-best level of debt level, and $d^f(r(I)) > d^c$.*

Panel A of Figure 3 illustrates the debt policy functions corresponding to the three-state example of Figure 2. Corollary 1 and Panel A of Figure 3 demonstrate the advantages of measuring debt relative to the endowment share of the young. The debt policy functions depend only on the current debt d and are independent of the current endowment share s. There is a common threshold level of debt d^c, below which each debt policy function is flat and above which the debt policy function is increasing. For $d \leq d^c$, the debt policy function $b_r(d) = d^0(r)$, which is the debt that maximizes the payoff to the planner, analogously to $\omega^0(r)$. The reason why the debt policy function is independent of s can be seen from Lemmas 2 and 3. When the participation constraint of the young binds, there is a single variable function h_r such that the policy function for the promised utility satisfies $g_r(s, \omega) = h_r(\log(1 - \exp(\omega)) - \log(s))$. With $\exp(\omega) = 1 - s + sd$, the promised utility, and hence, debt next period, depends only on $\log(1 - d)$.[27] By Assumption 3, the minimum debt $d_{\min} = 0$ and by Assumption 4, the maximum debt $d_{\max} < 1$.

The Dynamics of Debt. The dynamics of debt follow from the debt policy functions described in Corollary 1 and the history of endowment shares. Panel A of Figure 3 shows that for $d > d^c$, debt is drawn down or repaid when the endowment share of the young next period is $r(1)$ or $r(2)$. If, for example, there are enough consecutive occurrences of the endowment state 1, then debt falls to zero. Since such sequences occur with positive probability, debt is reset to zero periodically. If, on the other hand, the endowment share of the young next period is $r(3)$, then

[26] For the sake of brevity, in what follows we often refer to $d(x)$ simply as outstanding debt without the caveat that it is measured relative to the endowment share of the young.

[27] For CRRA preferences with a coefficient of risk aversion greater than one, the same property applies with a different normalization of debt that depends on the coefficient of risk aversion.

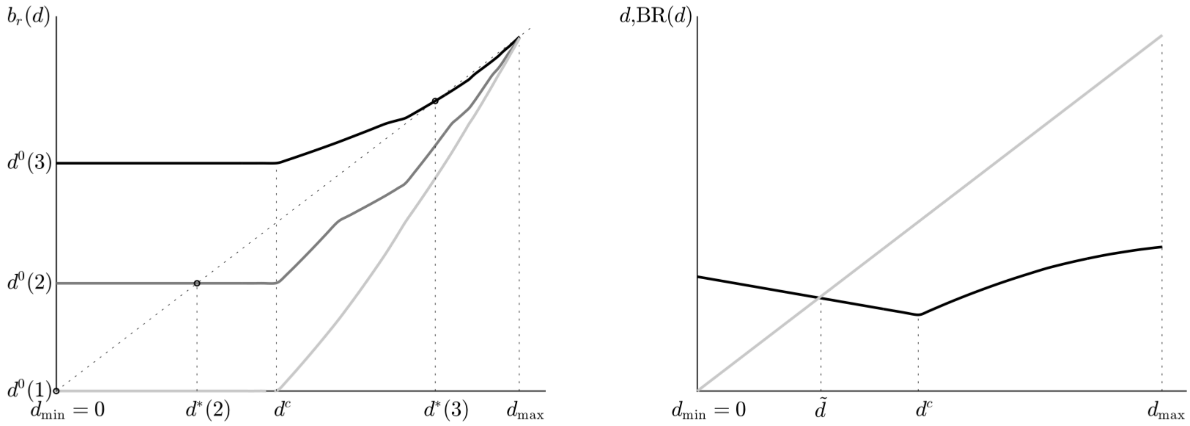

Figure 3: Panel A – Debt Dynamics. Panel B – Fiscal Reaction Function.

Note: The illustration is for the case $I = 3$ corresponding to the example in Figure 2. Panel A plots the optimal debt rule as a function of d. The light gray line is $b_1(d)$, the dark gray line is $b_2(d)$, and the black line is $b_3(d)$. The level $d^*(3)$ is the largest sustainable debt and $d^*(1)$ is the lowest sustainable debt within the ergodic set. Panel B plots the fiscal reaction function as the difference between $\mathrm{BR}(d)$ represented by the dark gray line and d represented by the light gray line.

the debt rises for $d < d^*(3)$ but falls for $d > d^*(3)$. Thus, any debt $d > d^*(3)$ is transitory and cannot occur in the long run.[28] For $d \leq d^c$, the debt policy function is independent of the current debt d and depends only on the endowment share of the young next period. Part (iii) of Corollary 1 shows that when the same endowment share is repeated, then debt converges to a fixed point that corresponds to the first-best debt level, $d^*(s)$. In Panel A of Figure 3, if the endowment share $s(3)$ reoccurs consecutively, then the debt converges to $d^*(3)$. In summary, debt will rise or fall depending on the endowment share of the young next period and the current debt that encapsulates the history of endowment shares.

Fiscal Reaction Function. The fiscal reaction function shows how the tax rate depends on debt. Since the promised utility and debt are monotonically related, we abuse notation and rewrite the state space as $x = (s, d)$.[29] With logarithmic preferences, the intertemporal marginal rate of substitution is $m(x, x') = \beta s(1 - d)/(1 - r(1 - b_r(d)))$, where $x = (s, d)$ is the current state and $x' = (r, b_r(d))$ is the next-period state. Since the endowment shares are i.i.d., the transition probability is $\pi(x, x') = \pi(r)$ and given debt d, the current young can be thought as buying $rb_r(d)$ bonds contingent on a next-period endowment share of r at the price of $q(x, x') = \pi(r)m(x, x')$ to finance their future consumption. The bond purchases generate a bond revenue for the planner of $\sum_r q(x, x')rb_r(d)$. Measured relative to the endowment share of the current young, the bond revenue depends only on the current debt d:

$$\mathrm{BR}(d) := \left(\frac{1}{s}\right) \sum\nolimits_r q(x, x')rb_r(d) = \beta \sum\nolimits_{r \in \mathcal{I}} \pi(r) \left(\frac{1 - d}{1 - r(1 - b_r(d))}\right) rb_r(d).$$

[28] In general, if $d^*(I) < d_{\max}$, then any $d \in [d^*(I), d_{\max})$ is transitory.

[29] Note that $\omega = \log(1 - s + sd)$ so this is a translation of the state space (s, ω).

The planner finances the current debt liability d by a combination of taxes (or subsidies) on the young and bond revenue $\mathrm{BR}(d)$. Hence, the budget constraint of the planner is:

$$\tau(d) = d - \mathrm{BR}(d), \tag{16}$$

where $\tau(d)$ is the tax rate on the current young, measured as a share of their endowment. We refer to $\tau(d)$ as the *fiscal reaction function* and $s\tau(d)$ as the *primary fiscal balance*. A positive value of $s\tau(d)$ corresponds to a primary fiscal surplus whereas a negative value of $s\tau(d)$ corresponds to a primary fiscal deficit.

Panel B of Figure 3 plots the outstanding debt d and the bond revenue $\mathrm{BR}(d)$ with the fiscal reaction function $\tau(d)$ given by the difference between the two lines. The properties of $\mathrm{BR}(d)$ are complex because $b_r(d)$ is increasing in d whereas the state price $q((s,d),(r,b_r(d)))$ is decreasing in d and b_r. By Proposition 2, there are transfers next-period for any debt $d < d_{\max}$ and hence, $\mathrm{BR}(0)$ is strictly positive. Moreover, since $b_r(d)$ is constant for debt below the threshold level, $\mathrm{BR}(d)$ is linearly decreasing in d for $d < d^c$. Hence, the fiscal reaction function $\tau(d)$ is linearly increasing in d for $d < d^c$. There is an intersection point $\tilde{d}$ where $\tau(\tilde{d}) = 0$. For $d < \tilde{d}$, bond revenue exceeds the current debt allowing a subsidy to be paid to the young, that is, there is a fiscal deficit. For $d > \tilde{d}$, bond revenue is insufficient to cover the current debt and the planner imposes a tax on the young, that is, there is a fiscal surplus. For $d > d^c$, a rise in d leads to more bond issuance but the price of the bonds decreases with debt. Thus, the net effect of a change in d on bond revenue is generally ambiguous. For the example illustrated in Panel B, the fiscal reaction function $\tau(d)$ is increasing in d but initially at a slower rate for debt above the threshold level and then at a higher rate when debt is large.

At the first-best solution, the fiscal reaction function is increasing and linear in d.[30] Thus, the non-linearity of the fiscal reaction function is a result of the participation constraints. There is a large literature that examines the non-linearity of the fiscal reaction function both theoretically and empirically (see, for example Mendoza and Ostry, 2008, Ghosh et al., 2013, among many others). The literature finds some evidence that the fiscal reaction function is non-linear in d. Our model shows how non-linearity can occur in an optimizing model with enforcement frictions.[31]

[30] Ignoring the non-negativity constraint on transfers, the first-best fiscal reaction function is $\tau^*(d) = (1-a)+ad$ where $a = (1-\delta) + (\beta+\delta)\mathbb{E}_s s$ and $\mathbb{E}_s s$ is the expected endowment share. Since $\mathbb{E}_s s > \delta/(\beta+\delta)$, $a > 1$.

[31] An important issue addressed by the literature is *fiscal fatigue* where the primary fiscal balance responds more slowly to rising debt, particularly at high levels of debt. This slowing in the response is associated with adverse implications of debt including the risk of default. In our model, there is no default although the non-linearity is similarly driven by limited enforcement constraints.

7 Asset Pricing Implications

In this section, we examine the asset pricing implications of the model.[32] In an overlapping generations model, the growth-adjusted stochastic discount factor is given by the intertemporal marginal rate of substitution $m(x,x') := \beta u_c(1-c(x'))/u_c(c(x))$ where x is the current state, x' is the state next period, $u_c(c(x))$ is the marginal utility of the current young and $u_c(1-c(x'))$ is their marginal utility when old. This stochastic discount factor can be decomposed into two components:

$$m(x,x') = \underbrace{\delta\left(\frac{u_c(c(x'))}{u_c(c(x))}\right)}_{m_A(x,x')}\underbrace{\left(\frac{\beta}{\delta}\frac{u_c(1-c(x'))}{u_c(c(x'))}\right)}_{m_B(x,x')}. \tag{17}$$

The first component $m_A(x,x')$ represents risk sharing *across* two adjacent generations of the young and the second component $m_B(x,x')$ represents risk sharing *between* the young and the old at a given date. In a representative agent model, $m(x,x') = m_A(x,x')$ and the variability in the stochastic discount factor is determined by the variability of consumption, which in an endowment economy depends on the variability of the aggregate endowment. In contrast, in an overlapping generations model, if there is variability in the degree of risk sharing between the young and the old, then there is variability in $m_B(x,x')$, which interacts with the variability in $m_A(x,x')$ with consequent implications for asset pricing. In the optimal sustainable intergenerational insurance, the variability of $m_B(x,x')$ is determined by the first-order condition (12) and the updating rule (15). This variability depends on the current endowment share and the outstanding debt. To simplify the discussion, we confine attention to states in the ergodic set and suppose for simplicity that the boundary constraints on debt do not bind.[33]

Let Q denote the matrix of state prices $q(x,x') = \pi(r)m(x,x')$ where $x = (s,d)$ and $x' = (r, b_r(d))$, and let ϱ and ψ be the Perron root and corresponding eigenvector of Q. The Ross Recovery Theorem (Ross, 2015) shows that the k-period stochastic discount factor $m^k(x,x') = \varrho^k\psi(x)/\psi(x')$ where ϱ and $\psi(x)$ can be interpreted as the discount factor and inverse marginal utility of a pseudo-representative agent. Using the first-order condition (12) and the updating rule (15), $f(x')/(1-f(x')) = (\delta/\beta)(1+\mu(x'))/(1+\mu(x))$ where $f(x) = s(1-d)$

[32] We follow several authors in addressing asset pricing in overlapping generations models (see, for example, Huberman, 1984, Huffman, 1986, Labadie, 1986) and Gârleanu and Panageas (2023) for a recent contribution.

[33] Limiting the analysis to the ergodic set is justified for two reasons. First, there is convergence to the ergodic set within finite time, as shown in Section 5. Second, absent constraint (4), the planner sets the initial debt to $d_{\min}$, which lies in the ergodic set. Although it is restrictive to assume that the bounds on debt are non-binding, it simplifies the analysis and we will mention how results are changed when the bounds are binding. Furthermore, we assume that the ergodic set is finite for simplicity and because it corresponds to our numerical procedures. Nevertheless, it is possible to adapt the arguments to the denumerable case and to more general state spaces (see, for example, Hansen and Scheinkman, 2009, Christensen, 2017).

is the consumption of the young and $\mu(x)$ is the multiplier on the corresponding participation constraint. To ease notation, let $\nu(x) := 1 + \mu(x)$ and $\nu_{\max} := \max_x \nu(x)$. Since we show below that $\varrho = \delta$, it follows from equation (17) that $\psi(x) = f(x)/\nu(x)$.[34] The unit price of a k-period discount bond in state x, $p^k(x)$, is given by the corresponding row sum of Q^k, the k-fold matrix power of Q. The corresponding yield is $y^k(x) := -(1/k)\log(p^k(x))$ and the yield on the long bond is $y^\infty(x) := \lim_{k\to\infty} y^k(x)$.

Martin and Ross (2019) shows that $|y^k(x) - y^\infty(x)| \leq (1/k)\Upsilon$ for $\Upsilon := \log(\psi_{\max}/\psi_{\min})$ where $\psi_{\max}$ and $\psi_{\min}$ are the maximum and minimum values of ψ. That is, Υ measures the range of the eigenvector and places a bound on the deviation of the yield from its long-run value. A low value of Υ means that the yield curve is relatively flat and that yields are not very sensitive to debt.[35]

The matrix Q is the growth-adjusted or de-trended state price matrix. Let $q_+^k(x, x')$ and $m_+^k(x, x')$ denote the unadjusted state prices and marginal rate of substitution conditional on state x when the state k-periods ahead is x' and the growth factor is γ. It can be checked that $q_+^k(x, x') = \varsigma(\gamma)\bar{\gamma}^{-k}(\bar{\gamma}/\gamma)q^k(x, x')$ and $m_+^k(x, x') = \bar{\gamma}^{-k}(\bar{\gamma}/\gamma)m^k(x, x')$ where $q^k(x, x') = \pi^k(x, x')m^k(x, x')$ and $m^k(x, x') = \varrho^k\psi(x)/\psi(x')$.[36] Letting $y_+^k(x)$ be the yield on the k-period bond in the unadjusted case, we can establish the following proposition.

Proposition 6. *For each $x \in E$: (i) The yield on a k-period bond $y_+^k(x) = y^k(x) + \log(\bar{\gamma})$. (ii) The yield on the long bond $y_+^\infty(x) = y^\infty + \log(\bar{\gamma})$ with $y^\infty = -\log(\delta)$. (iii) The yield $y^k(x)$ is increasing in d for each s and k. (iv) The long-short spreads on yields satisfy $y^\infty - y^1(1, d^*(1)) > 0 > y^\infty - y^1(I, d^*(I))$. (v) The measure $\Upsilon = \log(\nu_{\max})$ where $\nu_{\max} = \nu(I, d^*(I))$.*

Part (i) of Proposition 6 shows that the difference between the yields in the growth-adjusted and unadjusted cases is simply the average growth rate as measured by $\log(\bar{\gamma})$, independently of the current state x or the time horizon k. This is similar to the result of Krueger and Lustig (2010), which shows that market risk premia are unaffected by the market incompleteness in a model with infinitely-lived agents and uninsurable idiosyncratic as well as aggregate risk. This independence occurs because the growth shocks are i.i.d. and hence, each generation faces the same growth risk. Part (ii) follows from the result of Martin and Ross (2019) that $y^\infty = -\log(\varrho)$,

[34] The multiplicative decomposition of $\psi(x)$ into the components $f(x)$ and $1/\nu(x)$ is reminiscent of a number of other asset pricing models (see, for example, Bansal and Lehmann, 1997).

[35] The bound Υ provides a measure of the residual risk. Two alternative measures used to assess how risk is shared are the insurance coefficient (see, for example, Kaplan and Violante, 2010) and a consumption equivalent welfare change (see, for example, Song et al., 2015). We discuss these alternatives in Part C of the Supplementary Appendix and show that these two measures have similar comparative static properties to the bound Υ.

[36] With stochastic growth, the Ross Recovery Theorem does not recover the true probability transition matrix $\pi^k(x, x')$. Instead, it recovers a transition matrix where probabilities are weighed by the relative growth factors (see, for example, Hansen and Scheinkman, 2012).

independently of x and the fact that $\varrho = \delta$ if the upper bound and non-negativity constraints do not bind.[37] To understand Part (iii), note that the consumption share of the young is decreasing in d and that, since $b_r(d)$ is increasing in d from Corollary 1, the consumption share of the old next period is increasing in d. Hence, the intertemporal marginal rate of substitution $m(x, x')$ is decreasing in d. For a given x, the transition probabilities do not depend on d and hence, the price of the one-period discount bond is decreasing in d, equivalently, its yield is increasing in d. Thus, an agent born into a generation with higher debt faces higher one-period yields. Since bond prices are linked recursively, the same property holds for bonds of any maturity.

Part (iv) of Proposition 6 shows that the long-short spread $y^\infty - y^1(x)$ is positive when the young have a low endowment share and the debt is low. In this case, it follows from Section 6 that debt is likely to increase in the future and hence, yields are expected to increase in the future with growing debt. Conversely, the spread is negative when the young have a high endowment share and debt is high, in which case, debt as well as yields are likely to fall in the future. Part (v) shows that Υ is determined by the multiplier $\nu_{\max}$, which corresponds to the fixed point of the debt policy function in the highest endowment state when the debt is $d^*(I)$. That is, the bound on the variability of the yield curve is determined by the most binding participation constraint, which occurs for the largest debt in the ergodic set.

8 Debt Valuation

The budget constraint (16) can be iterated forward to show that current debt equals the present value of all future primary surpluses. As shown by Bohn (1995), the present value includes a risk premium component that determines the economy's fiscal capacity to sustain debt. Jiang et al. (2021) show that the risk premium on public debt in the U.S. is too low compared to the risk premium on future primary surpluses. That is, there is mispricing of public debt, a *debt valuation puzzle*. In this section, we provide an additional perspective on this puzzle by considering the one-period multiplicative risk premium on debt.

If the endowment share of the young next-period is r and the growth rate is γ, then debt next period is $rb_r(d)\gamma e$. Since the value of the bonds issued today is $s\mathrm{BR}(d)e$, the return on debt is $R_+(x, x') = rb_r(d)\gamma/(s\mathrm{BR}(d))$. With these returns, the multiplicative risk premium is $\mathrm{MRP}_+(d) = (\bar{R}_+(x) - R_+^f(x))/R_+^f(x)$ where $\bar{R}_+(x)$ is the expected return on debt and $R_+^f(x)$ is the risk-free rate on interest in state x. It can be shown that this multiplicative risk premium is independent of s and has the following properties.

[37] If the upper bound constraint does not bind, then $\varrho \leq \delta$ and if the non-negativity constraints do not bind, then $\varrho \geq \delta$.

Proposition 7. *The multiplicative risk premium $MRP_+(d) = MRP(d) + \alpha(d)MRP^*$, where $\alpha(d) = \bar{R}(x)/R^f(x)$, $MRP(d)$ is the multiplicative risk premium in the absence of growth and MRP^* is the multiplicative risk premium with complete risk sharing. The components satisfy: (i) $MRP(d) \leq 0$; (ii) $0 \leq \alpha(d) \leq 1$; and (iii) $MRP^* = (\mathbb{E}_\gamma \gamma - \bar{\gamma})/\bar{\gamma} \geq 0$.*

Proposition 7 shows that the multiplicative risk premium has a linear decomposition that depends on the multiplicative risk premium with complete risk sharing and the multiplicative risk premium without growth. This decomposition follows because the growth shocks and the shocks to endowment shares are independent. The term MRP^* is the risk premium with complete risk sharing due only to the growth shocks. It is positive because the growth rate is negatively correlated with the future marginal utility under complete insurance. In particular, the expected return is proportional to the expected growth factor $\mathbb{E}_\gamma \gamma$, and the risk-free return is proportional to the harmonic mean $\bar{\gamma}$. If there is uncertainty in the growth factors, then the arithmetic mean is larger than the harmonic mean, that is, $\mathrm{MRP}^* > 0$. This risk premium is the same as the risk premium on aggregate risk, for example, the risk premium on the Lucas-tree asset.

Absent growth shocks, the multiplicative risk premium $\mathrm{MRP}(d)$ is negative when there are binding participation constraints. Let $R(x, x')$ denote the return on debt without growth shocks. Since $x' = (r, b_r(d))$ and $b_r(d)$ is increasing in r, it follows that $R(x, x')$ is also increasing in r. From Lemma 2, the consumption of the old falls with r and hence, the corresponding marginal utility is increasing with r. Since the debt is high when the marginal utility is high, debt has a negative risk premium. This risk premium is negative because debt is state contingent and provides partial insurance. It can be checked that $\alpha(d) = \bar{R}(x)/R^f(x)$ is independent of s and because the risk premium is negative, $0 < \alpha(d) < 1$.

Since $\mathrm{MRP}_+(d) = \mathrm{MRP}(d) + \alpha(d)\mathrm{MRP}^*$, $\mathrm{MPR}_+(d) = \mathrm{MRP}^*$ and $\alpha(d) = 1$ when there is complete risk sharing. However, if the participation constraints bind, then $\alpha(d) < 1$, $\mathrm{MRP}(d) < 0$ and $\mathrm{MRP}_+(d) < \mathrm{MRP}^*$ for each d. That is, the risk premium on debt is lower than the risk premium on aggregate risk. Convenience yields and seigniorage have been offered as potential explanations of the debt valuation puzzle. If risk sharing is partial and debt has an insurance value, then this should also be taken into account in explaining why the risk premium on debt appears to be low. The size of this effect depends on d. Although the dependence on d may be complex, the example considered in Section 9 shows that $\mathrm{MRP}_+(d)$ is increasing in d.

9 Two-State Example

Finding the optimal sustainable intergenerational insurance is complex because it involves solving the functional equation of problem P1. In this section, we present an example with

$I = 2$ that can be solved using a simple shooting algorithm.[38] For this case, we solve for the invariant distribution and derive a closed-form solution for the Martin-Ross measure Υ. We also consider the implications of a demographic shock.

Suppose there are two possible endowment shares for the young: $s(1) = \kappa - \epsilon(1-\pi)/\pi$ and $s(2) = \kappa + \epsilon$, where $\pi = \pi(1)$, $\kappa \geq 1/2$ and $\epsilon > 0$. That is, the young are poor in state 1 and rich in state 2. An increase in ϵ is a mean-preserving spread of the risk.

By Assumptions 3 and 4, $d^*(2) > d^0(2) > d^c > d^0(1) = d^*(1) = 0$. From Corollary 1, the debt policy functions satisfy $b_2(d) > b_1(d)$. We make two additional assumptions.

Assumption 5. *(i)* $d^*(2) < d_{\max}$*; and (ii)* $b_1(d^*(2)) < d^c$.

Part (i) of Assumption 5 implies that the upper debt limit never binds. By Part (ii), debt is below d^c whenever state 1 occurs. In such a case, the history of endowment states is forgotten once state 1 occurs and the dynamics of debt depend only on the number of consecutive state 2s in the most recent history, starting from the resetting level $d^0(r)$. The longer is the sequence of state 2s, the larger is the level of debt, approaching $d^*(2)$ if state 2 is repeated infinitely often. The set of parameter values that satisfy Assumption 5 as well as Assumptions 2-4 is non-empty with the following belonging to this set.

Example 1. $\delta = \beta = \exp(-1/75)$, $\pi = 1/2$, $\kappa = 3/5$, *and* $\epsilon = 1/10$.

Example 1 is our canonical example and all figures in this section relate to this case. To simplify notation, let $d^{(n)}(s)$ be the debt in state s after n previous consecutive state 2s, where $d^{(0)}(s) = d^0(s)$ are the resetting levels and $\lim_{n\to\infty} d^{(n)}(2) = d^*(2)$. Under Assumption 5, the invariant distribution of debt is a transformation of a geometric distribution and the bound Υ has a closed-form solution.

Proposition 8. *Under Assumption 5: (i) The ergodic set* $E = \{(s, d^{(n)}(s))_{n\geq 0, s=1,2}\}$ *with a probability mass function* $\phi(s, d^{(n)}(s)) = \phi(s, d^0(s))(1-\pi)^n$ *for* $n \geq 1$ *where* $\phi(1, d^0(1)) = \pi^2$ *and* $\phi(2, d^0(2)) = \pi(1-\pi)$*. (ii)* $\Upsilon = \log(\delta/\beta) - \log(\chi^{-1} - 1)$ *where*

$$\chi = \left(\frac{\delta}{\beta}\right)^{\frac{1-\pi}{\pi}} \left(\frac{\beta+\delta}{\delta}\right)^{\frac{1+\beta(1-\pi)}{\beta\pi}} (\kappa+\epsilon)^{\frac{1}{\beta\pi}} (1-\kappa-\epsilon)^{\frac{1-\pi}{\pi}} \left(1-\kappa+\epsilon\frac{1-\pi}{\pi}\right).$$

Since debt is reset to $d^0(s)$ after an occurrence of state 1, the invariant distribution of the pair (s, d) depends only on the number of consecutive state 2s. Therefore, the invariant distribution is a transformation of a geometric distribution. As stated in part (i) of Proposition 8, the

[38] Initially, we assume no growth but the numerical exercises below incorporate stochastic growth. See Part D of the Supplementary Appendix for details of the shooting algorithm.

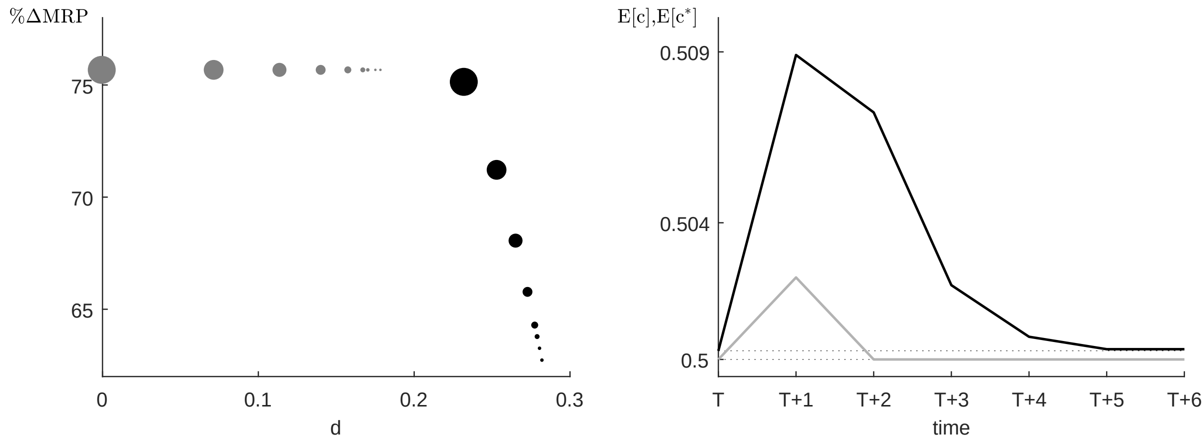

Figure 4: Panel A – Multiplicative Risk Premium Panel B – Demographic Shock.

Note: Panel A plots $(\mathrm{MRP}^* - \mathrm{MRP}_+(d))/\mathrm{MRP}^*$ for the values of d in the ergodic set. Gray dots correspond to state 1 and the black dots to state 2. The size of each dot indicates the frequency of occurrence. Panel B plots the impulse response functions to a demographic shock, showing the average consumption shares of the young both for the limited enforcement (dark gray) and full enforcement case (light gray). The average is computed starting from the invariant distribution and recomputing the average for all possible sample paths.

invariant distribution has a probability mass of $\phi(1, d^0(1)) = \pi^2$ and $\phi(2, d^0(2)) = \pi(1 - \pi)$ at the regeneration states and zero probability mass at states $(s, b_s(d^*(2)))$. Furthermore, low debt levels occur only in state 1, while high levels occur only in state 2.

Part (ii) of Proposition 8 provides a closed-form solution for the bound Υ. From Proposition 6, the bound is strictly positive and determined by the tightness of the participation constraint of the young when $x = (2, d^*(2))$. Using this closed-form solution, it is easily checked that Υ decreases with the discount factors β or δ, that is, as either the agent or the planner become more patient. Moreover, Υ decreases with the average endowment share to the young, κ and increases with risk, ϵ.[39]

Panel A of Figure 4 illustrates the impact of debt on the risk premium in a version of Example 1 with stochastic growth. In this example, the arithmetic mean growth rate is set to 4% and the corresponding multiplicative risk premium is approximately 5%. Proposition 7 shows that $\mathrm{MRP}^* > \mathrm{MRP}_+(d)$ and Panel A of Figure 4 shows that the gap is constant when debt is low, but decreases with debt when debt is high. The intuition is that at high levels of debt, future debt varies less across endowment states. Since the risk premium on the debt is substantially lower than the risk premium on the aggregate risk, this implies that the planner does not need to accumulate substantial surpluses in the future to maintain its intertemporal budget constraint. This is especially true when debt is low and the effect is ameliorated when debt is already high.

[39] In Part C of the Supplementary Appendix, we present the comparative static properties of Υ also for parameter values that violate Assumption 5.

Demographic Change. Finally, we illustrate how the economy responds to the arrival of unexpected demographic shock. Consider a one-off increase in fertility at date $T + 1$. That is, suppose the cohort size is $N_t = 1$ for $t \leq T$ and $N_t = 1 + \varepsilon$ for $t > T$. The ratio of young to old is $N_t/N_{t\text{-}1}$, which equals $1 + \varepsilon$ for $t = T + 1$ and equals one otherwise. Moreover, suppose that the endowment is proportional to the population size, so that the total endowment is $e_t^y N_t + e_t^o N_{t-1}$, and that the planner's weights placed on the utility of the young and the old are adjusted by the group sizes. Panel B of Figure 4 shows the impulse response function to a demographic shock of $\varepsilon = 0.05$. The initial increase in the birth rate implies a larger weight on the young and a larger amount of total endowment to be shared at date $T + 1$. Under full enforcement (light gray line), the consumption share of the young rises because more weight is placed on their consumption. However, the effect lasts only for one period and the consumption share reverts back to its long-run value in the next period. With limited enforcement, the effect is amplified and persists for several periods. This is because a positive fertility shock relaxes the current participation constraint, leading to both increased consumption for the current young and reduced future promises. As a result, it also loosens participation constraints in the future, thereby prolonging the impact of the temporary demographic shock across several periods.[40]

10 Conclusion

The paper has developed a theory of intergenerational insurance in a stochastic overlapping generations model with limited enforcement of risk sharing transfers. Despite the stationarity of the underlying economic environment, it has been shown that generational risk is spread across future generations in ways that create history dependence of transfers with periodic resetting, at which time the history of shocks is forgotten. By interpreting intergenerational insurance in terms of public debt, we provide a theory of the dynamics of debt that offers a new perspective on the fiscal reaction function and the sustainability and valuation of public debt. With complete insurance, the fiscal reaction function is linear and the risk premium on public debt equals the risk premium on aggregate risk. When the participation constraints bind and intergenerational insurance is incomplete, the fiscal reaction function is non-linear and the risk premium on public debt is below the risk premium on aggregate risk.

The results suggest several potential directions for future research. Firstly, the model has no heterogeneity within a generation. Enriching the demographic structure of the model, either by having more than two overlapping generations or allowing for heterogeneity within the same generation, would make it possible to address the interdependence between intergenerational

[40] This positive demographic shock is equivalent to an exogenous unexpected decrease in the fiscal burden on the young and therefore, it is similar to the effects caused by shocks to expenditures or, in an economy with prices, by inflationary shocks, which erode the value of debt to repay.

and intra-generational insurance. Secondly, introducing a technology to transform endowments from one date to another would make it possible to study the interplay between self-insurance and intergenerational insurance. Thirdly, the model could be extended to allow for non-independent and correlated shocks.

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Online Appendix (Proofs of Main Results)

This Appendix contains the proofs of the main results. Omitted proofs can be found in Part B of the Supplementary Appendix.

Proof of Lemma 2.

(i) Since the constraint set $\Phi(s,\omega)$ is convex and the objective function is strictly concave, the policy function $g_r(\omega,s)$ is single-valued and continuous in ω. Let $h_s(\omega) := -(\delta/\beta)V_\omega(s,\omega)$ where $h\colon \Omega(s) \to [\lambda_{\min}(s), \lambda_{\max}(s)]$ with $\lambda_{\min}(s) = \max\{0, ((\delta/(\beta+\delta)) - s)/((\beta/(\beta+\delta))s)\}$. Let $h_s^{-1}\colon [\lambda_{\min}(s), \lambda_{\max}(s)] \to \Omega(s)$ be its inverse. By the concavity of the frontier $V(s,\omega)$ in ω, $h_s^{-1}(\lambda)$ is strictly increasing in λ for $\lambda > \lambda_{\min}(s)$. Suppose first that $\omega \geq \omega^0(s)$. Hence, from (7), $f(s,\omega) = 1 - \exp(\omega)$. Since $g_r(s,\omega) = \max\{\omega_{\min}(r), \min\{\omega_{\max}(r), h_r^{-1}(\mu(s,\omega))\}\}$, substituting into (11), there is a unique value (possibly zero) of μ that satisfies the constraint. If $\mu(s,\omega) = 0$, then $g_r(s,\omega) = \omega^0(r)$ for each share r. If $\mu(s,\omega) > 0$, then $\mu(s,\omega)$ is strictly increasing in ω since $f(s,\omega)$ is strictly decreasing in ω and $h_r^{-1}(\mu)$ is increasing in μ. Thus, $g_r(s,\omega)$ is strictly increasing in ω for $g_r(s,\omega) \in (\omega^0(r), \omega_{\max}(r))$. If $\omega < \omega^0(s)$, then $\lambda(s,\omega) = 0$ and hence, since $f(s,\omega)$ is independent of ω, $g_r(s,\omega)$ is also independent of ω.

(ii) Consider states $s(i) > s(i-1)$, $i = 2, \ldots, I$. For brevity, write $g_r(i,\omega)$ for $g_r(s(i),\omega)$ and $g_i(s,\omega)$ for $g_{r(i)}(s,\omega)$ etc. We first show that $\mu(i,\omega) \geq \mu(i-1,\omega)$ for $\omega \in [\omega_{\min}(i-1), \omega_{\max}(i)]$ with a strict inequality unless $\mu(i,\omega) = \mu(i-1,\omega) = 0$. Suppose to the contrary that $\mu(i-1,\omega) \geq \mu(i,\omega) > 0$. It follows from (12) that $g_r(i-1,\omega) \geq g_r(i,\omega)$. Using (11) and $\hat{v}(s) = \log(s) + \beta\sum_r \pi(r)\log(1-r)$, gives

$$\log(f(i-1,\omega)) - \log(f(i,\omega)) = (\hat{v}(i-1) - \hat{v}(i)) + \beta\sum_r \pi(r)\left(g_r(i,\omega) - g_r(i-1,\omega)\right).$$

Since $\hat{v}(i-1) - \hat{v}(i) < 0$ and $g_r(i,\omega) - g_r(i-1,\omega) \leq 0$, $f(i,\omega) > f(i-1,\omega)$ and $\log(1 - f(i-1,\omega)) > \log(1 - f(i,\omega)) \geq \omega$. Hence, $\lambda(i-1,\omega) = 0 \leq \lambda(i,\omega)$. However, since $\lambda(i,\omega) \geq \lambda(i-1,\omega)$ and $\mu(i-1,\omega) \geq \mu(i,\omega)$, it follows from (12) that $f(i-1,\omega) \geq f(i,\omega)$, a contradiction. Hence, if $\mu(i-1,\omega) = \mu(i,\omega) = 0$, then $g_r(i-1,\omega) = g_r(i,\omega) = \omega^0(r)$ independently of s. If, however, $\mu(i-1,\omega) > 0$, then it follows from (12) that $g_r(i-1,\omega) < g_r(i,\omega)$ for $\omega \in [\omega_{\min}(i-1), \omega_{\max}(i)]$. By Assumption 3, $\mu(1,\omega^0(1)) = 0$ and by Assumption 4, $\mu(I,\omega^0(I)) > 0$. Since $\mu(s,\omega)$ is increasing in ω, $\mu(I,\omega^0(I)) > 0$ and $\mu(I,\omega) > \mu(1,\omega)$ for $\omega \in (\omega^0(1), \omega_{\max}(I))$. It then follows from (13) that $V_\omega(r, g_r(I,\omega)) < V_\omega(r, g_r(1,\omega))$ and therefore, from the strict concavity of $V(r,\omega)$ in ω for $\omega > \omega^0(1) \geq \omega^0(r)$ that $g_r(I,\omega) > g_r(1,\omega)$.

Next consider two states $i > i-1$, $i = 2, \ldots, I$. If $g_i(x) \leq \omega^0(i-1)$ or $g_{i-1}(x) \geq \omega_{\max}(i)$, then $g_{i-1}(x) \geq g_i(x)$. Therefore, suppose $g_i(x), g_{i-1}(x) \in (\omega^0(i-1), \omega_{\max}(i))$. We first show that $V_\omega(i-1,\omega) \geq V_\omega(i,\omega)$ for $\omega \in (\omega^0(i-1), \omega_{\max}(i))$. For $\omega > \omega^0(i-1)$, it follows that $\lambda(i-1,\omega) > 0$ and since $\omega^0(i-1) \geq \omega^0(i)$, $\lambda(i-1,\omega) > 0$. Therefore, $f(i,\omega) = f(i-1,\omega)$. In this case, it follows from above that $\mu(i,\omega) \geq \mu(i-1,\omega)$ with equality only if $\mu(i,\omega) = \mu(i-1,\omega) = 0$. Hence, it follows from (12) that $\lambda(i-1,\omega) \leq \lambda(i,\omega)$ with strict inequality if $\mu(i,\omega) > 0$. Using (14), it follows that $V_\omega(i-1,\omega) \geq V_\omega(i,\omega)$ with strict inequality if $\mu(i,\omega) > 0$. For $g_i(x), g_{i-1}(x) > \omega^0(i-1)$, $\eta_i(x) = \eta_{i-1}(x) = 0$ and for $g_i(x), g_{i-1}(x) < \omega_{\max}(i)$, $\xi_i(x) = \xi_{i-1}(x) = 0$. Hence, it follows from (13) that $V_\omega(i, g_i(s,\omega)) = V_\omega(i-1, g_{i-1}(s,\omega))$. Since $V_\omega(i-1,\omega) \geq V_\omega(i,\omega)$, it follows from the concavity of $V(\cdot,\omega)$ in ω that $g_{i-1}(s,\omega) \geq g_i(s,\omega)$. The inequality is strict if $V_\omega(i-1,\omega) > V_\omega(i,\omega)$ by the strict concavity of $V(\cdot,\omega)$ in ω. Since $\mu(I,\omega) > \mu(1,\omega)$ for $\omega \in (\omega^0(1), \omega_{\max}(I))$, $V_\omega(1,\omega) > V_\omega(I,\omega)$ and hence, $g_1(s,\omega) > g_I(s,\omega)$.

(iii) Since $\mu(1,\omega^0(1)) = 0$ and $f(1,\omega^0(1)) = s(1)$ it follows that $g_r(1,\omega^0(1)) = \omega^0(r)$ for each r. Since $\omega^0(r) > \omega_{\min}(r)$ for at least some r, it follows that (11) is strictly slack and there is some $\omega^c > \omega^0(1)$ such that (11) is non-binding with $g_r(1,\omega) = \omega^0(r)$ for each r and $\omega \in [\omega^0(1), \omega^c]$.

(iv) It follows from (12) that for $\omega = \omega^*(s) > \omega_{\min}(s)$, $\mu(s,\omega) = \lambda(s,\omega)$. In this case, $V_\omega(s,\omega^*(s)) = V_\omega(r, g_r(s,\omega^*(s)))$ for $g_r(s,\omega^*(s)) \in (\omega^0(r), \omega_{\max}(r))$, and, in particular, $g_s(s,\omega^*(s)) = \omega^*(s)$, so that $\omega^*(s)$ is a fixed point of the mapping $g_s(s,\omega)$. Equally, for $\omega < \omega^*(s)$, it follows from (12) that $\mu(s,\omega) > \lambda(s,\omega)$, so that from the concavity of the frontier, $g_s(s,\omega) > \omega^*(s)$. Likewise, for $\omega > \omega^*(s)$, it follows from (12) that $\mu(s,\omega) < \lambda(s,\omega)$, so that from the concavity of the frontier, $g_s(s,\omega) < \omega^*(s)$. If $\omega^*(s) = \omega_{\min}(s)$, then $f(s,\omega) = s$ and $\mu(s,\omega^*(s)) = 0$ by Assumption 2. Hence, $g_s(s,\omega^*(s)) = \omega^*(s)$. Since $\omega^0(s)$ is decreasing in s, it follows by Assumption 4 that $\omega^0(I) < \omega^f(I) \leq \omega^*$. ■

Proof of Lemma 3.

(i) For $\omega > \omega^0(s)$, $\lambda(s,\omega) > 0$ and therefore, it follows from (7) that $f(s,\omega) = 1 - \exp(w)$. For $\omega = \omega^0(s)$, either $\lambda(s,\omega^0(s)) > 0$ or $\lambda(s,\omega^0(s)) = 0$. In either case, it follows from (7) or the definition of $\omega^0(s)$ that $f(s,\omega^0(s)) = 1 - \exp(w^0(s))$. For $\omega < \omega^0(s)$, it follows that $\lambda(s,\omega) = 0$. From (12), let $\phi(s,\mu) = \min\{\delta(1+\mu)/(\beta+\delta(1+\mu)), s\}$ where $\phi(s,\mu)$ is increasing in μ with $\phi(s,0) = c^*(s)$. Recall that $h_r^{-1}(\mu)$, defined in the proof of Lemma 2, satisfies $V_\omega(r, h_r^{-1}(\mu)) = -(\beta/\delta)\mu$ where $g_r(s,\omega) = \max\{\omega_{\min}(r), \min\{\omega_{\max}(r), h_r^{-1}(\mu(s,\omega))\}\}$. Since $h_r^{-1}(\mu)$ is increasing in μ, it follows from (11) that when $f(s,\omega^0(s)) = 1 - \exp(w^0(s))$, there is a unique value of μ, say $\mu^0(s)$ that solves the constraint. Furthermore, $\omega^0(s) = \log(1 - \phi(s,\mu^0(s)))$.

(ii) Since $\hat{v}(i) > \hat{v}(i-1)$, it follows from Part(i) that $\mu^0(i) \geq \mu^0(i-1)$ with strict inequality if $\mu^0(i) > 0$. Therefore, since $\phi(s,\mu)$ is strictly increasing in μ and independent of s for $\mu > 0$, $c^0(i) \geq c^0(i-1)$ with strict inequality if $\mu^0(i) > 0$. By Assumption 4, $\mu^0(I) > 0$ and by Assumption 3, $\mu^0(1) = 0$. Hence, $c^0(I) > c^0(1)$.

(iii) Lemma 2 establishes that at the fixed point, $\omega^f(s) = \min\{\omega_{\max}(s), \omega^*(s)\}$. Hence, $f(s,\omega^f(s)) \leq c^*(s)$ with equality for $\omega^f(s) < \omega_{\max}(s)$. ■

Proof of Proposition 5. Using the properties of $g_r(x)$ from Lemma 2 and the argument in the text, it can be seen that there is an $k \geq 1$ and $\epsilon > 0$ such that $P^k(x, \{x_0\}) > \epsilon$ for each $x \in \mathcal{X}$ and any x_0. Hence, it follows that Condition **M** of Stokey et al. (1989, page 348) is satisfied. Therefore, Theorem 11.12 of Stokey et al. (1989) applies and there is strong convergence. Non-degeneracy with $|E| > I$ follows from Assumption 4. The finiteness of the return times follows from Lemma 2(iii) and the finiteness of $\mathcal{I}$. The relationship between the probability mass and the expected return times and the pointwise convergence is standard (see, for example, Theorems 10.2.3 and 13.1.2 of Meyn and Tweedie, 2009). ■

Proof of Proposition 6.

(i) Since $q_+^k(x,x') = \varsigma(\gamma)\bar{\gamma}^{-k}(\bar{\gamma}/\gamma)q^k(x,x')$, summing over x' and γ, the unadjusted bond prices are $p_+^k(x) = \bar{\gamma}^{-k}p^k(x)$. Hence, the yields satisfy $y_+^k(x) = y^k(x) + \log(\bar{\gamma})$.

(ii) It is a standard result (see, for example, Martin and Ross, 2019) that $\lim_{k\to\infty} y^k(x) = \mathbb{E}_\phi[\log(m(x,x'))] = \log(\varrho)$, where $\mathbb{E}_\phi$ is the expectation taken over the invariant distribution of x and ϱ is the Perron root of the matrix Q. Taking logs of equation (17), $\log(m(x,x')) = \log(\beta) + \log(c(x)) - \log(1 - c(x'))$. Using equation (12) and the updating rule (15), assuming the non-negativity constraints and the upper bound constraint do not bind, gives $\log(c(x')) - \log(1 - c(x')) = -\log(\beta/\delta) + \log(\nu(x')) - \log(\nu(x))$, where $\nu(x) = 1 + \mu(x)$. Therefore, $\log(m(x,x')) = \log(\delta) + \log(c(x)) - \log(c(x')) + \log(\nu(x')) - \log(\nu(x))$. Taking expectations at the invariant distribution, $\mathbb{E}_\phi[\log(m(x,x'))] = \log(\delta)$. Hence, $\varrho = \delta$ and $\lim_{k\to\infty} y_+^k(x) = \log(\delta) + \log(\bar{\gamma})$.

(iii) Recall that $m(x,x') = m((s,d),(r,b_r(d))) = \beta s(1-d)/(1 - r(1 - b_r(d)))$. Since $b_r(d)$ is increasing in d by Corollary 1, it follows that $m(x,x')$ is decreasing in d. The price of a one-period discount bond in state (s,d) is $p^1(s,d) = \sum_r \pi(r)m((s,d),(r,b_r(d)))$, which is also decreasing in d. Making the induction hypothesis that the price of a k-period discount bond is decreasing in d, $p^{k+1}(s,d) = \sum_r \pi(r)m((s,d),(r,b_r(d)))p^k(r,b_r(d))$. Since $p^k(s,d)$ and $m((s,d),(r,b_r(d)))$ are positive and decreasing in d, and $b_r(d)$ is increasing in d, it follows that $p^{k+1}(s,d)$ is decreasing d. Hence, the conditional yield $y^k(s,d) = -(1/k)\log(p^k(s,d))$ is increasing in d for each s and k.

(iv) From Corollary 1, the fixed points of the mappings of $b_r(d)$ are $d^*(r)$ when the upper bound constraint does not bind, and that consumption is at the first-best at these fixed points. Hence, $m((s,d^*(s)),(s,d^*(s))) = \delta$. By Lemma 2, the consumption of the old decreases with r. Hence, $m((1,d^*(1)),(r,b_r(d^*(1)))) \geq \delta$ with a strict inequality for some r. Taking expectations, the bond price $p^1(1,d^*(1)) > \delta$ and consequently, the yield $y^1(1,d^*(1)) < -\log(\delta)$. Since $y^\infty = -\log(\delta)$, $y^\infty - y^1(1,d^*(1)) > 0$. Likewise, it can be checked that $m((I,d^*(I)),(r,b_r(d^*(I)))) \leq \delta$ with a strict inequality for some r, which shows that $y^\infty - y^1(I,d^*(I)) < 0$.

(v) By Definition $\Upsilon = \log(\psi_{\max}/\psi_{\min})$ where $\psi_{\max}$ and $\psi_{\min}$ are the maximum and minimum values of the eigenvector of the matrix Q. Using equations (12) and (15) and assuming the non-negativity and upper bound constraints do not bind, $m_B(x,x') = \nu(x')/\nu(x)$. Since $m_A(x,x') = \delta f(x)/f(x')$, the eigenvector $\psi(x) = f(x)/\nu(x)$. Since $f(x') = \delta\nu(x)/(\beta\nu(x) + \delta\nu(x'))$, it follows that $\psi(x') = \delta/(\beta\nu(x) + \delta\nu(x'))$. The maximum value of $\psi(x')$ occurs when $\nu(x) = \nu(x') = 1$, in which case $\psi_{\max} = \delta/(\beta+\delta)$. The minimum value occurs when $\nu(x) = \nu(x') = \nu_{\max}$, in which case $\psi_{\min} = \delta/((\beta+\delta)\nu_{\max})$. Hence, $\Upsilon = \log(\psi_{\max}/\psi_{\min}) = \log(\nu_{\max})$. It is easily checked that $\nu(s,d)$ is increasing in d with $\nu(s,d^0(s))$ increasing in s, so that for $(s,d) \in E$, $\nu_{\max} = \nu(I,d^*(I))$. ■

Proof of Proposition 7. With $R(x,x') = rb_r(d)/(s\mathrm{BR}(d))$, the expected return is $\bar{R}(x) = \sum_r \pi(r)rb_r(d)/(s\mathrm{BR}(d))$. The risk-free rate is $R^f(x) = (\sum_r q(x,x'))^{-1}$ where $q(x,x') = \pi(r)\beta s(1-d)/(1-r(1-b_r(d))$. It follows therefore, that $\bar{R}(x)/R^f(x)$ is independent of s. Since the risk-adjusted return on any asset is equal to the risk-free return, $\mathrm{MRP}(d) = -\mathrm{cov}(m(x,x'),R(x,x'))$ where $m(x,x') = q(x,x')/\pi(r)$. From Corollary 1, $b_r(d)$ is increasing in r and hence, $R(x,x')$ is increasing with r. From Lemma 2, old consumption $(1-r(1-b_r(d)))$ falls with r and hence, $m(x,x')$ is increasing with r. Hence, if risk sharing is incomplete, the covariance term is positive and $\mathrm{MRP}(d) < 0$. That is, $\bar{R}(x)/R^f(x) < 1$. With growth shocks, $R_+(x,x') = R(x,x')\gamma$ and $q_+(x,x') = \varsigma(\gamma)q(x,x')/\gamma$. Hence, $\bar{R}_+(x) = \bar{R}(x)(\mathbb{E}_\gamma\gamma)$ and $R_+^f(x) = R^f(x)\bar{\gamma}$. Therefore,

$$\mathrm{MRP}_+(d) = \frac{\bar{R}_+(x) - R_+^f(x)}{R_+^f(x)} = \left(\frac{\bar{R}(x)}{R^f(x)} - 1\right) + \left(\frac{\bar{R}(x)}{R^f(x)}\right)\left(\frac{\mathbb{E}_\gamma\gamma}{\bar{\gamma}} - 1\right).$$

Let $R_+^*(x,x')$ denote the returns with complete risk sharing. It is easy to check that

$$R_+^*(x,x') = \frac{\left(r - \frac{\delta}{\beta+\delta}\right)\gamma}{\delta\left(\sum_r \pi_r r - \frac{\delta}{\beta+\delta}\right)}.$$

The corresponding expected return is $\bar{R}_+^*(x) = (\mathbb{E}_\gamma \gamma)/\delta$. Likewise, $q_+^*(x,x') = \delta\varsigma(\gamma)\pi(r)/\gamma$, so that the risk-free return is $R_+^{f*} = \bar{\gamma}/\delta$. Hence, the corresponding multiplicative risk premium is $\text{MRP}^* = (\mathbb{E}_\gamma\gamma - \bar{\gamma})/\bar{\gamma}$. Since the arithmetic mean is larger than the harmonic mean, $\text{MRP}^* > 0$. Substituting into the above equation, we have $\text{MRP}_+(d) = \text{MRP}(d) + \alpha(d)\text{MRP}^*$, where $\alpha(d) = \bar{R}(x)/R^f(x)$, as required. ■

Proof of Proposition 8.

(i) Since the probability of endowment state 1 is π and debt is reset to the regeneration levels $d^0(s)$ after endowment state 1 has occurred, the probability that the state $(s, d^0(s))$ occurs is $\phi(s, d^0(s)) = \pi(s)\pi$, irrespective of the date or history. Therefore, T periods after such a resetting, the distribution function is:

$$\phi_T(s, d^{(n)}(s)) = \phi(s, d^0(s))(1-\pi)^n \quad \text{for} \quad n = 0, 1, 2, \ldots, T-1,$$

with $\phi_T(s, d^{(T)}(s)) = \pi(s)(1-\pi)^T$. Taking the limit as $T \to \infty$ gives the invariant distribution ϕ described in the text.

(ii) By Proposition 6, $\Upsilon = \log(\nu_{\max})$. The value of $\nu_{\max}$ can be found from the fixed point of the mapping $b_2(d)$, which occurs at $d = d^*(2)$. From the first-order condition (12), $\log(\nu_{\max}) = \log(\delta/\beta) + \log((s(1)(1-b_1(d^*(2))))^{-1} - 1)$. Since the participation constraint is binding when $d = d^*(2)$ and $b_2(d^*(2)) = d^*(2)$, $b_1(d^*(2))$ can be found by solving:

$$\log(1-d^*(2)) + \beta\left(\pi \log\left(1 - s(1) + s(1)b_1(d^*(2))\right) + (1-\pi)\log\left(1 - s(2) + s(2)d^*(2)\right)\right)$$
$$= \beta\left(\pi\log\left(1-s(1)\right) + (1-\pi)\log\left(1-s(2)\right)\right).$$

Since $s(1) = \kappa - \epsilon(1-\pi)/\pi$ and $s(2) = \kappa + \epsilon$, setting $\chi = 1 - s(1)(1 - b_1(d^*(2)))$ and using $d^*(2) = 1 - \delta/(s(2)(\beta+\delta))$ gives the result in the text. ■

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Supplementary Appendix

This appendix presents supplementary material referenced in the paper. Part A provides evidence on the relative income of the young and the old for six OECD countries referred to in footnote 2 in the Introduction. Part B provides proofs of Propositions 2 and 4 from Sections 2 and 3 together with the proof of Lemma 1 from Section 4. Part C examines two alternative welfare measures, the insurance coefficient and consumption-equivalent welfare change measure and provides some comparative static results for the two-state example of Section 9. Part D presents the shooting algorithm used to derive the optimal allocation in Section 9. Part E describes the pseudo-code for the numerical algorithms used in the paper.

A Change in Relative Income of Young and Old

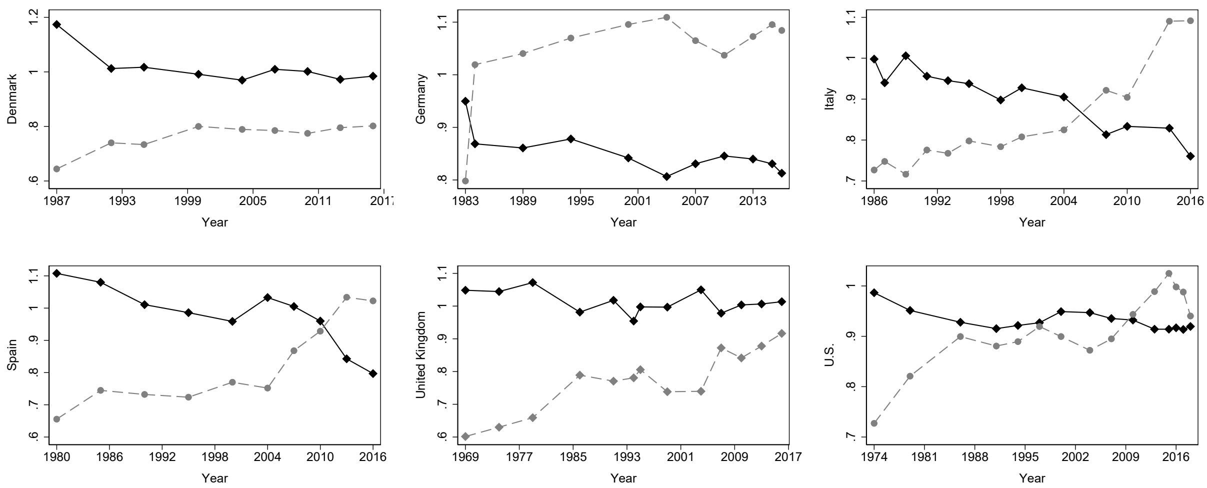

Figure A.1: Relative Income of Young and Old for six OECD Countries

Note: The solid line is the average net (of taxes and transfers) equivalized disposable income for individuals aged 25-34 divided by the average of the same measure for the whole population. The dotted line is the corresponding ratio for individuals aged 65-74.

Figure A.1 illustrates the average disposable income of individuals aged 25-34 (the young) and the average disposable income of individuals aged 65-74 (the old) relative to the national average over recent decades for Denmark, Germany, Italy, Spain, U.K. and U.S. (data periods are country specific). Data is taken from the Luxembourg Income Study Database available at `www.lisdatacenter.org`. In each country there has been an improvement in the average disposable income of the old compared to the average disposable income of the young over the sample period. For example, the average disposable income of the young in the U.S. has fallen from just below the national average to just above 90% of the national average during 1974-2018. Over the same period, the old have fared much better with their average disposal income rising from approximately 70% of the national average to become roughly equal to the national average. Moreover, the old overtook the young for the first time around the time of the financial crisis of 2008.

A similar pattern can be seen in Italy and Spain and a narrowing of the gap between the young and the old can also be observed in Denmark and the U.K. Germany is somewhat different with the old overtaking the young as early as the 1980s.

B Omitted Proofs

Proof of Proposition 2. Here, we consider the case without growth shocks, so that $\bar{\gamma} = 1$. The lifetime endowment utility of an agent born in a state with endowment share s is:

$$\hat{v}(s) := \log(s) + \beta \sum_r \pi(r) \log(1 - r).$$

Consider a small transfer $\mathrm{d}\tau(s)$ in state s from the young to the old. The problem of existence of a sustainable allocation can be answered by finding a vector of positive transfer $\mathrm{d}\tau$ such that there is a weak improvement over the lifetime endowment utility in all states and a strict improvement in at least one state. The change in the lifetime endowment utility induced by a vector $\mathrm{d}\tau$ is non-negative if

$$-s^{-1}\mathrm{d}\tau(s) + \beta \sum_r \pi(r)(1 - r)^{-1}\mathrm{d}\tau(r) \geq 0. \tag{B.1}$$

Rearranging (B.1) in terms of the marginal rates of substitution $\hat{m}(s, r)$, we have:

$$-\mathrm{d}\tau(s) + \sum_r \pi(r)\hat{m}(s, r)\mathrm{d}\tau(r) \geq 0.$$

The problem of existence can then be addressed by finding a vector $\mathrm{d}\tau > 0$ that solves:

$$\left(\hat{Q} - I\right) \mathrm{d}\tau \geq 0, \tag{B.2}$$

where I is the identity matrix and $\hat{Q}$ is the matrix of $\hat{q}(s, r) = \pi(r)\hat{m}(s, r)$. Equation (B.2) has a well-known solution. Using the Perron-Frobenius theorem, there exists a strictly positive solution for $\mathrm{d}\tau$, provided that the Perron root, that is, the largest eigenvalue of $\hat{Q}$, is greater than one. This is satisfied by Assumption 2, which guarantees the existence of positive transfers from the young to the old that improve the utility of each generation. ∎

Proof of Proposition 4. Let $\omega_0^c = \omega^*$ and define the critical utility ω_1^c by:

$$\log(1 - \exp(\omega_1^c)) + \beta\omega^* = \hat{v} := \log(s) + \beta\log(1 - s).$$

Define ω_n^c recursively by:

$$\log(1 - \exp(\omega_n^c))) + \beta\omega_{n-1}^c = \hat{v} \quad \text{for } n = 2, 3, \ldots, \infty.$$

From the strict concavity of the logarithmic utility function $\omega_n^c > \omega_{n-1}^c$ and $\lim_{n\to\infty} \omega_n^c = \omega_{\max} = \log(s)$. Let $v^* = \log(1 - \exp(\omega^*)) + (\beta/\delta)\omega^*$. With some abuse of notation, let $V_n(\omega)$ denote the value function when $\omega \in (\omega_{n-1}^c, \omega_n^c]$. Hence,

$$V_n(\omega) = \log(1 - \exp(\omega)) + \frac{\beta}{\delta}\omega + \delta V_{n-1}\left(\frac{1}{\beta}\left(\hat{v} - \log(1 - \exp(\omega))\right)\right).$$

For $\omega \leq \omega^*$, $\omega' = \omega^*$. Therefore, $V(\omega) = v^*/(1 - \delta)$ for $\omega \in [\omega_{\min}, \omega^*]$. For $\omega \in (\omega^*, \omega_1^c]$,

$$V_1(\omega) = \log(1 - \exp(\omega)) + \frac{\beta}{\delta}\omega + \frac{\delta}{1 - \delta}v^*.$$

Differentiating the function $V_1(\omega)$ gives:

$$\frac{\mathrm{d}V_1(\omega)}{\mathrm{d}\omega} = \frac{\beta}{\delta} - \frac{\exp(\omega)}{1 - \exp(\omega)}.$$

Let $h(\omega) := \exp(\omega)/(1 - \exp(\omega))$. Since $\omega > \omega^*$, $h(\omega) > \beta/\delta$ and $\mathrm{d}V_1(\omega)/\mathrm{d}\omega < 0$. Note that $h(\omega^*) = \beta/\delta$ and therefore, in the limit as $\omega \to \omega^*$, $\mathrm{d}V_1(\omega)/\mathrm{d}\omega = 0$. Furthermore, the function $V_1(\omega)$ is strictly concave because $h(\omega)$ is increasing in ω. Using this result, we can proceed by induction and assume $V_{n-1}(\omega)$ is decreasing and strictly concave. Then, it is straightforward to establish that $V_n(\omega)$ is decreasing and strictly concave. Continuity follows since $\lim_{\omega\to\omega_n^c} V_{n+1}(\omega) = V_n(\omega_n^c)$. To establish differentiability, we need to demonstrate that:

$$\lim_{\omega\to\omega_n^c} \frac{\mathrm{d}V_{n+1}(\omega)}{\mathrm{d}\omega} = \frac{\mathrm{d}V_n(\omega_n^c)}{\mathrm{d}\omega}.$$

To show this, note that for $\omega \in (\omega_n^c, \omega_{n+1}^c)$:

$$\frac{\mathrm{d}V_{n+1}(\omega)}{\mathrm{d}\omega} = \frac{\beta}{\delta} - h(\omega)\left(1 - \frac{\delta}{\beta}\frac{\mathrm{d}V_n(\omega')}{\mathrm{d}\omega}\right).$$

Starting with $n = 1$, we have:

$$\lim_{\omega\to\omega_1^c} \frac{\mathrm{d}V_2(\omega)}{\mathrm{d}\omega} = \frac{\beta}{\delta} - h(\omega_1^c)\left(1 - \frac{\delta}{\beta}\lim_{\omega\to\omega_0^c}\frac{\mathrm{d}V_1(\omega)}{\mathrm{d}\omega}\right).$$

Since $\lim_{\omega\to\omega_0^c} \mathrm{d}V_1(\omega)/\mathrm{d}\omega = 0$, we have:

$$\lim_{\omega\to\omega_1^c} \frac{\mathrm{d}V_2(\omega)}{\mathrm{d}\omega} = \frac{\beta}{\delta} - h(\omega_1^c) = \frac{\mathrm{d}V_1(\omega_1^c)}{\mathrm{d}\omega}.$$

Therefore, make the recursive assumption that $\lim_{\omega\to\omega_{n-1}^c} \mathrm{d}V_n(\omega)/\mathrm{d}\omega = \mathrm{d}V_{n-1}(\omega_{n-1}^c)/\mathrm{d}\omega$. In general, we have:

$$\begin{aligned}\lim_{\omega\to\omega_n^c} \frac{\mathrm{d}V_{n+1}(\omega)}{\mathrm{d}\omega} &= \frac{\beta}{\delta} - h(\omega_n^c)\left(1 - \frac{\delta}{\beta}\lim_{\omega\to\omega_{n-1}^c}\frac{\mathrm{d}V_n(\omega)}{\mathrm{d}\omega}\right)\\ \frac{\mathrm{d}V_n(\omega_n^c)}{\mathrm{d}\omega} &= \frac{\beta}{\delta} - h(\omega_n^c)\left(1 - \frac{\delta}{\beta}\frac{\mathrm{d}V_{n-1}(\omega_{n-1}^c)}{\mathrm{d}\omega}\right).\end{aligned}$$

By the recursive assumption, these two equations are equal. Hence, we conclude that $V(\omega)$ is differentiable. In particular, repeated substitution gives:

$$\frac{\mathrm{d}V_n(\omega_n^c)}{\mathrm{d}\omega} = \frac{\beta}{\delta} - \left(\frac{\delta}{\beta}\right)^{n-1} \prod_{j=1}^{n} h(\omega_j^c).$$

Since $h(\omega_j^c) \in [\beta/\delta, s/(1-s))$, taking the limit as $n \to \infty$, or equivalently, $\omega \to \omega_{\max}$, gives $\lim_{\omega\to\omega_{\max}} \mathrm{d}V(\omega)/\mathrm{d}\omega = -\infty$. Equation (6) follows from above given that $\omega' = \omega^*$ or satisfies $\log(1-\exp(\omega)) + \beta\omega' = \hat{\upsilon}$ if $\log(1-\exp(\omega)) + \beta\omega^* < \hat{\upsilon}$. ∎

Proof of Lemma 1.

(i) Given the participation constraint of the old, $\omega \geq \omega_{\min}(s) = \log(1-s)$. The largest feasible ω, $\omega_{\max}$, can be found by solving the set of equations $\log(1 - \exp(\omega_{\max}(s))) + \beta\sum_r \pi(r)\omega_{\max}(r) = \hat{\upsilon}(s)$. There is a trivial solution where $\omega_{\max}(s) = \omega_{\min}(s)$ but by Proposition 2 there is also a non-trivial solution with $\omega_{\max}(s) > \omega_{\min}(s)$ for each s. Since the utility function is concave, this non-trivial solution is unique. Let $\Delta\varpi := \sum_r \pi(r)(\omega_{\max}(r) - \omega_{\min}(r))$. Then, $\omega_{\max}(s)$ can be found by solving the set of equations $\log(1 - \exp(\omega_{\max}(s))) - \log(1 - \exp(\omega_{\min}(s))) + \beta\Delta\varpi = 0$. Since $\Delta\varpi > 0$ by Proposition 2, it follows that $\omega_{\max}(s) > \omega_{\min}(s)$ for all s. A reduction in ω, enlarges the constraint set $\Phi(s,\omega)$ of Problem P1 and hence, $V(s,\omega)$ is non-increasing in ω. To show that $V(s,\omega)$ is concave in ω, consider the mapping T where

$$(TJ)(s,\omega) = \max_{\{c,(\omega_r)_{r\in\mathcal{I}}\}\in\Phi(s,\omega)} \frac{\beta}{\delta}\log(1-c) + \log(c) + \delta\sum_r \pi(r)J(r,\omega_r).$$

Consider $J = V^*$, the first-best frontier. Proposition 3 established that $V^*(s,\omega)$ is concave in ω. It follows from the definitions of T and V^* that $TV^*(s,\omega) \leq V^*(s,\omega)$ because $V^*(s,\omega) \leq v^*(s) + \delta\bar{V}^*$ and the mapping T adds the participation constraints (11). That is, $T^nV^*(s,\omega) \leq T^{n-1}V^*(s,\omega)$ for $n = 1$. Now, make the induction hypothesis that $T^nV^*(s,\omega) \leq T^{n-1}V^*(s,\omega)$ for $n \geq 2$ and apply the mapping T to the two functions $T^nV^*(s,\omega)$ and $T^{n-1}V^*(s,\omega)$. It is straightforward to show that $T^{n+1}V^*(s,\omega) \leq T^nV^*(s,\omega)$, because the constraint set is the same in both cases but, by the induction hypothesis, the objective is no greater in the former case. Hence, the sequence $T^nV^*(s,\omega)$ is non-increasing and converges. Let $V^\infty(s,\omega) := \lim_{n\to\infty} T^nV^*(s,\omega)$ be the pointwise limit of the mapping T. We have that V^∞ and V are both fixed points of T. Since the mapping is monotonic, $T^n(V^*) \geq T^n(V) = V$. Hence, $V^\infty \geq V$ but, since V is the maximum, we have that $V^\infty = V$. Starting from V^*, the objective function in the mapping T is concave because V^* and the utility function are concave. The constraint set $\Phi(s,\omega)$ is convex. Hence, $TV^*(s,\omega)$ is concave. By induction, $T^nV^*(s,\omega)$ and the limit function V are also concave. Differentiability follows because the linear independence constraint qualification is satisfied on the interior of the domain. There are $I + 1$ choice variables and $2I + 3$ constraints. Since V is concave, it is differentiable if the multipliers associated with the constraints are unique. The multipliers are unique if the linear independence constraint qualification is satisfied, that is, if the gradients of the binding constraints are linearly independent at the solution. Since $\omega_{\max}(s) > \omega_{\min}(s)$, the corresponding upper and lower bound constraints in (9) and (10) are not both active. Not all lower bound constraints in (10) are active because this would involve no transfers next period, which we know from Proposition 2 is not optimal. For $\omega < \omega_{\max}(s)$, not all upper bound constraints in (9) are active because this would imply that the participation constraint of the young (11) does not bind, in which case some ω_r can be lowered below $\omega_{\max}(r)$ to raise the planner's payoff. If $\omega > \omega_{\min}(s)$, then the non-negativity constraint (8) is not active. If $\omega = \omega_{\min}(s)$ and (8) binds, then the young participation constraint is not active. Hence, in either case, there are at most $I + 1$ active constraints. Since the marginal utility is strictly increasing, $\beta > 0$, and $\pi(s) > 0$ for each s, it can be checked that the matrix of active constraints has full rank. Hence, the multipliers are unique and $V(s,\omega)$ is differentiable in ω on $(\omega_{\min}(s), \omega_{\max}(s))$. Since $V(s,\omega)$ is concave and differentiable in ω, it is also continuously differentiable in ω.

(ii) If constraint (7) binds, then the frontier is strictly downward sloping. Strict concavity of V when V is strictly downward sloping follows since TV is strictly concave when the frontier is strictly downward sloping because of the strict concavity of the logarithmic utility function and the concavity of V. If $\omega^0(s) > \omega^*(s)$, then it would be possible to lower $\omega^0(s)$, increase consumption of the current young keeping all future promises the same without violating any constraints and increase the planner's utility. Assumption 4 guarantees that $\omega^0(s) < \omega^*(s)$ for at least one state s. If $\omega_{\min}(s) = \omega^*(s)$, then $\omega^0(s) = \omega^*(s)$ and hence, constraint (11) does not bind. Therefore, $\mu(s, \omega_{\min}(s)) = 0$. In this case, from equation (13), either $V_\omega(r, g_r(s, \omega)) = 0$ for $\omega = \omega_{\min}(s)$ or one of the constraints (9) or (10) binds and $g_r(s, \omega)$ is independent of ω. Therefore, in either case, $V_\omega(s, \omega^0(s)) = (\beta/\delta) - (\exp(\omega_{\min})/(1 - \exp(\omega_{\min}))) = (\beta/\delta) - ((1 - s)/s) \leq 0$. If $\omega_{\min}(s) < \omega^*(s)$, then it cannot be that $\omega^0(s) = \omega_{\min}(s)$ because this implies $c(s, \omega^0(s)) = s$, which, in turn, implies $\omega^0(s) \geq \omega^*(s)$ from equation (7), a contradiction. The multiplier $\lambda(s, \omega) \geq 0$ and since $V(s, \omega)$ is concave in ω, $\lambda(s, \omega)$ is increasing in ω. Let $\lambda_{\max}(s) := \lim_{\omega \to \omega_{\max}} \lambda(s, \omega)$, then $\lim_{\omega \to \omega_{\max}} V_\omega(s, \omega) = -(\beta/\delta)\lambda_{\max}(s)$, where $\lambda_{\max}(s) \in \mathbb{R}_+ \cup \{\infty\}$.

(iii) Since $\omega_{\min}(s) = \log(1 - s)$, it follows that $\omega_{\min}(s(i)) < \omega_{\min}(s(i - 1))$ for $i = 2, \ldots, I$. It follows from the proof of Part (i) that $\log(1 - \exp(\omega_{\max}(s))) - \log(1 - \exp(\omega_{\min}(s)))$ is independent of s. Therefore, $\omega_{\max}(s(i - 1)) > \omega_{\max}(s(i))$. Equally, $\Delta\varpi$ is bounded above since the endowment share is less than one in each state. Hence, $\omega_{\max}(s) < 0$, otherwise the constraint of the young cannot be satisfied. Since $\omega^0(s) = \log(1 - c^0(s))$, it follows from Lemma 3(ii) that $\omega^0(s(i)) \leq \omega^0(s(i - 1))$ with strict inequality for at least one i, and, hence, $\omega^0(I) < \omega^0(1)$. ∎

C Risk Measures and Comparative Statics

In this Appendix, we continue the two-state example of Section 9 and examine how the bound on the residual risk Υ and alternative measures of risk sharing respond to comparative statics changes of endowment parameters and discount factors. For all comparative statics, we change the value of the parameter of interest holding all other parameters at the values given in Example 1.[41]

The top row of Figure C.1 plots the bound Υ against κ, ϵ and δ, holding $\beta = \delta$ for relevant values of the parameters. A larger κ corresponds to a larger average endowment share to the young, while a smaller ϵ corresponds to reduced uncertainty. Increasing κ, or reducing ϵ, raises risk sharing as measured by a reduction in Υ. For κ above a critical value, or ϵ below a critical value, the first best is sustainable at the invariant distribution, in which case $\Upsilon = 0$.[42] The effect of changes in the discount factor on Υ is non-monotonic when we consider sufficiently low values of δ for which Assumption 5 does not hold. For high values of the discount factor, the invariant distribution has geometric probabilities as described in part (i) of Proposition 8. As the discount factor falls, either the current transfer is reduced, or the newly state-contingent

[41] In all cases, the invariant distribution is geometric, except when discount factors are changed. When the invariant distribution is not geometric, we can no longer rely on the shooting algorithm used in Section 9. In this case, we implement an algorithm based on a value function iteration method (see, Part E of the Supplementary Appendix for a description).

[42] The critical values are $\kappa \approx 0.6565$ and $\sigma \approx 0.0243$.

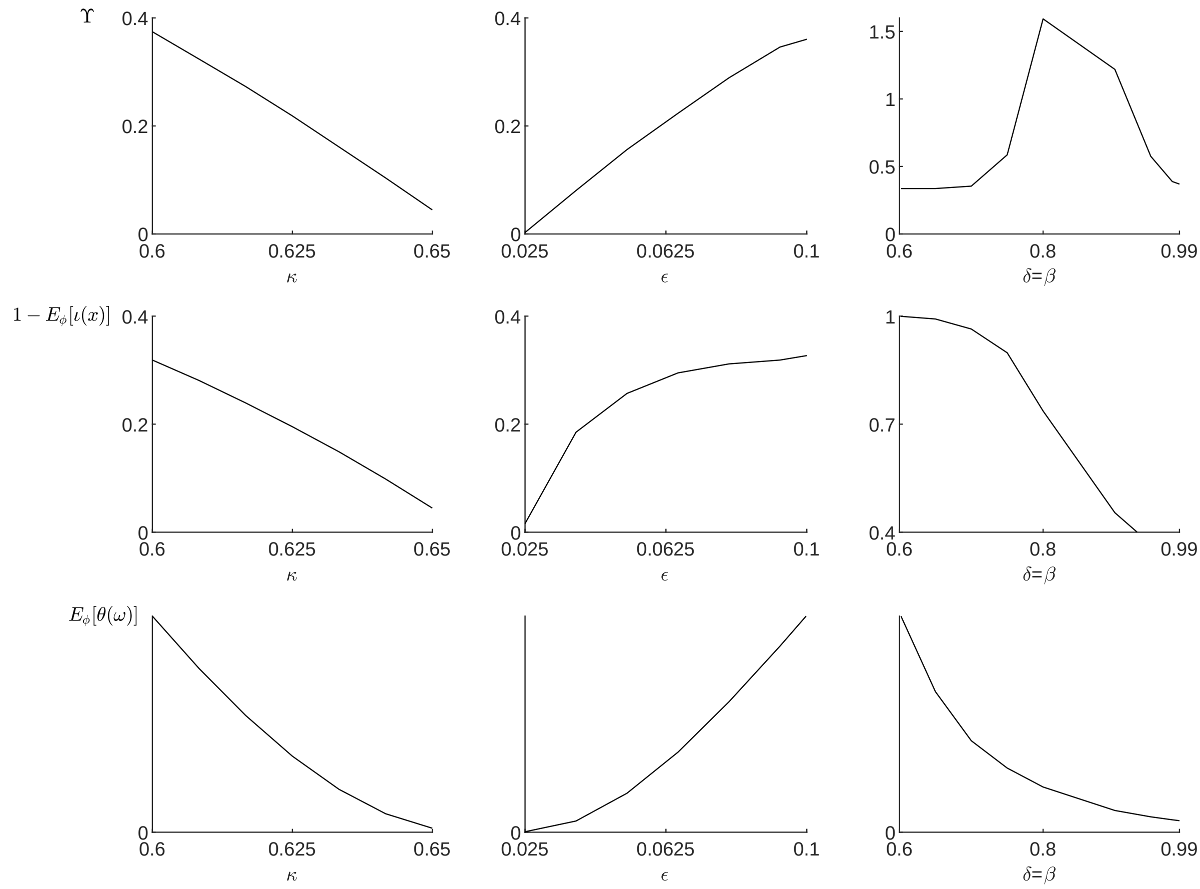

Figure C.1: Comparative Statics on the Bound Υ, the Insurance Coefficient and the Consumption Equivalent Welfare Change

Note: The top row illustrates the bound Υ. The middle row illustrates the average insurance coefficient $\mathbb{E}_{\phi}\left[\iota(x)\right]$. The bottom row illustrates the average consumption equivalent welfare change $\mathbb{E}_{\phi}\left[\theta(\omega)\right]$.

bonds increased, to satisfy the participation constraint of the young in state 2. This change reduces $d_{\max}$. However, since the change also raises $d^*(2)$, it effectively enlarges the ergodic set, resulting in an increase of risk, as reflected in the rise of Υ. As the discount factor is reduced further, the upper bound constraint on debt becomes binding and it is no longer true that resetting to the regeneration debt levels takes place any time state 1 occurs. Reversion to $d^0(r)$ occurs less frequently and the invariant distribution has now a positive probability mass at $d_{\max}$. The range $d_{\max} - d_{\min}$ decreases, implying that the bound Υ falls.

As alternative measures of risk sharing, we consider the *insurance coefficient* and the *consumption equivalent welfare change*, conditional on state $x = (s, d)$. The insurance coefficient $\iota(x)$ is the fraction of the variance of the endowment shock that does not translate into a corresponding change in consumption. With i.i.d. shocks, the insurance coefficient is:

$$\iota(x) = 1 - \frac{cov\left(\log\left(c(r, b_r(d))\right), \log(r)\right)}{var\left(\log(r)\right)}.$$

where r is the endowment shock next period. At the first best, and provided that the boundary constraints on debt do not bind, the consumption share of the young is independent of the state x and the insurance coefficient is one. The expected value of the one minus the insurance coefficient, evaluated at the invariant distribution, is plotted in the middle row of Figure C.1 against κ, ϵ and δ. This measure is smaller when more risk is shared. The consumption equivalent welfare change relative to the first best for a given $\omega := \sum_s \pi(s)\omega_s$ is measured by solving the following equation in terms of θ:

$$\frac{1}{1-\delta}\left(\mathbb{E}[u(c^*(1-\theta))] + \frac{\beta}{\delta}\mathbb{E}[u((1-c^*)(1-\theta))]\right) = \bar{V}(\omega),$$

where $\bar{V}(\omega) = \sum_s \pi(s)V(s,\omega_s)$. The solution $\theta(\omega)$ measures the proportion by which the first-best consumption needs to be reduced to match the optimal solution for each ω. The expected value of $\theta(\omega)$, evaluated at the invariant distribution, is plotted in the bottom row of Figure C.1 against κ, ϵ and δ. The consumption equivalent welfare change is smaller when more risk is shared. The long-run welfare loss measure is the average of $\theta(\omega)$ at the invariant distribution of ω. The comparative statics on the bound Υ are similar to those of the insurance coefficient and the consumption equivalent welfare. The amount of risk shared at the optimal solution increases with κ and δ (provided that the upper bound on debt does not bind) but falls with ϵ.

D Shooting Algorithm

In the two-state economy in Section 9, under Assumption 5, the optimal consumption depends only on the number of previous state 2s. Let $c^{(n)}(s)$ denote the consumption after n consecutive state 2s and let $\mu^{(n)}$ denote the corresponding multiplier on the state 2 participation constraint. It follows from the first-order condition (12) and the updating rule (15) that

$$c^{(n)}(1) = \frac{\delta}{\beta\nu^{(n-1)} + \delta} \quad \text{and} \quad c^{(n)}(2) = \frac{\delta\nu^{(n)}}{\beta\nu^{(n-1)} + \delta\nu^{(n)}} \quad \text{for } n = 0, 1, 2 \ldots, \infty,$$

where $\nu^{(n)} = 1 + \mu^{(n)}$ and $\nu^{(-1)} = 1$. Let $\nu^{(\infty)} = \lim_{n\to\infty} \nu^{(n)}$. The participation constraint of the young binds in state 2. Hence,

$$\log\left(\tfrac{\delta\nu^{(n)}}{\beta\nu^{(n-1)}+\delta\nu^{(n)}}\right) + \beta\left(\pi \log\left(\tfrac{\beta\nu^{(n)}}{\beta\nu^{(n)}+\delta}\right) + (1-\pi)\log\left(\tfrac{\beta\nu^{(n)}}{\beta\nu^{(n)}+\delta\nu^{(n+1)}}\right)\right) = \upsilon(2). \tag{D.1}$$

Since equation (D.1) holds in the limit

$$\log\left(\tfrac{\delta}{\beta+\delta}\right) + \beta\left(\pi \log\left(\tfrac{\beta\nu^{(\infty)}}{\beta\nu^{(\infty)}+\delta}\right) + (1-\pi)\log\left(\tfrac{\beta}{\beta+\delta}\right)\right) = \upsilon(2). \tag{D.2}$$

Since $v(2) = \log(s(2)) + \beta\pi \log(1 - s(1)) + (1 - \pi) \log(1 - s(2)))$, equation (D.2) can be solved to give:

$$\nu^{(\infty)} = \frac{\delta}{\beta}\left(-1+\left(\left(\frac{\delta}{\beta}\right)^{\frac{1-\pi}{\pi}}\left(\frac{\beta+\delta}{\delta}\right)^{\frac{1+\beta(1-\pi)}{\beta\pi}}(s(2))^{\frac{1}{\beta\pi}}(1-s(2))^{\frac{1-\pi}{\pi}}(1-s(1))\right)^{-1}\right)^{-1}. \quad \text{(D.3)}$$

Using equations (D.1) and (D.2), gives a second-order difference equation for $\nu^{(n)}$:

$$\nu^{(n+1)} = \frac{\beta}{\delta}\nu^{(n)}\left(-1+\left(\frac{\beta\nu^{(n)}}{\beta\nu^{(n)}+\delta}\right)^{\frac{\pi}{1-\pi}}\left(\frac{\beta\nu^{(\infty)}+\delta}{\beta\nu^{(\infty)}}\right)^{\frac{\pi}{1-\pi}}\left(\frac{\beta+\delta}{\delta}\right)^{\frac{1}{\beta(1-\pi)}}\left(\frac{\beta+\delta}{\beta}\right)\left(1+\frac{\beta}{\delta}\frac{\nu^{(n-1)}}{\nu^{(n)}}\right)^{-\frac{1}{\beta(1-\pi)}}\right). \quad \text{(D.4)}$$

It can be shown that the second-order difference equation in (D.4) has a unique saddle path solution. Since $\nu^{(-1)} = 1$, the solution can be found by a *forward shooting* algorithm to search for $\nu^{(0)}$ such that the absolute difference between $\nu^{(\infty)}$ (given in (D.3)) and $\nu^{(N+1)}$ (given in (D.4)) is sufficiently close to zero for N sufficiently large.

E Pseudo-code for Numerical Algorithms

Algorithms are implemented in MATLAB®. At each iteration, the optimization uses the nonlinear programming solver command `fsolve` in Algorithm 1 and command `fmincon` in Algorithm 2. Value function interpolation uses the spline method of the `interp1` command. In a typical example, the value function converges within 300 iterations.

Algorithm 1: Shooting Algorithm

procedure ▹ Find $\nu^{(0)} = 1 + \mu^{(0)}$ in two state economy (Section 9)
  target ← $\nu^{(\infty)}$ ▹ Use equation (D.3) in Appendix D
  tolerance ← $\epsilon > 0$ ▹ $\epsilon = 10^{-10}$
  repeat
    initialization ← $\nu_0^{(0)} > 0$
    Compute $\nu_0^{(N)}$ for $N = 20$ ▹ Use equation (D.4) in Appendix D
    $d \leftarrow d(\nu_0^{(N)}, \nu^{(\infty)})$ ▹ $d(\nu_0^{(N)}, \nu^{(\infty)}) = |\nu_0^{(N)} - \nu^{(\infty)}|$
  until $d < \epsilon$
  $\nu^{(0)} \leftarrow \nu_0^{(0)}$
end procedure

Algorithm 2: Find Value and Policy Functions

```
procedure                                   ▹ Find solution to functional equation (P1)
    Ω ← [ω_min, ω_max]                      ▹ ω_min and ω_max computed
    gridpoints ← gp                         ▹ Discretize Ω: gp = 200 Chebyshev interpolation points
    tolerance ← ϵ > 0                       ▹ ϵ = 10^−6
    J ← V*                                  ▹ V* is first best
    repeat
        Compute TJ from J                   ▹ Use equation (P1) and interpolate
        d ← d(TJ, J)                        ▹ d(TJ, J) = max_ω |TJ(ω) − J(ω)|
        J ← TJ
    until d < ϵ
    V ← J
    Compute g_r(s, ω) and f(s, ω)           ▹ Using the function V just computed.
end procedure
```

Algorithm 3: Computing the Invariant Distribution

```
procedure                                   ▹ Find invariant distribution for x = (s, ω) ∈ X ⊂ ℝ^{nI×1}
    initialization ← a_0 = e(1/nI)          ▹ e = (1, 1, ..., 1) ∈ ℝ^{nI×1}
    Compute a = Πa_0                        ▹ Use the transition probability Π ⊂ ℝ^{nI×nI}
    tolerance ← ϵ > 0                       ▹ ϵ = 10^−8
    repeat
        Compute a = Πa                      ▹ a is eigenvector associated with 1
        d ← d(Πa, a)                        ▹ d(Πa, a) = max_x |Πa(x) − a(x)|
        a ← Πa
    until d < ϵ
    ϕ ← a/∑_x a(x)                          ▹ ϕ is normalized invariant distribution
end procedure
```