

The distribution of wealth and redistributive policies *

Jess Benhabib	Alberto Bisin
Department of Economics	Department of Economics
New York University	New York University

This draft: March 2006-Preliminary

Abstract

We study the dynamics of the distribution of wealth in an Overlapping Generation economy with bequest and various forms of redistributive taxation. We characterize the transitional dynamics of the wealth distribution as well as the stationary distribution. We show that the stationary wealth distribution is a Pareto distribution whose statistical properties depend on fiscal policies. It can therefore be characterized by a single parameter (if population is constant), which is univocally related to the Gini coefficient of the distribution of wealth. We study analytically the dependence of the distribution of wealth, of wealth inequality in particular, on various redistributive fiscal policy instruments like capital income taxes, estate taxes, and the form and extent of welfare subsidies. Wealth is less concentrated (the Gini coefficient is lower) for both higher capital income taxes and estate taxes, but the marginal effect of capital income taxes is much stronger than the effect of estate taxes. Finally, we characterize optimal redistributive taxes with respect to a utilitarian social welfare measure. Social welfare is maximized short of minimal wealth inequality and with zero estate taxes.

*We gratefully acknowledge conversations with Alberto Bressan, Gianluca Clementi, Mariacristina De Nardi, Raquel Fernandez, Xavier Gabaix, Leslie Greengard, Frank Hoppensteadt, Boyan Jovanovic, John Leahy, Omar Licandro, Tom Sargent, Gianluca Violante, and Ed Wolff. Thanks to Nicola Scalzo and Eleonora Patacchini for help with "impossible" Italian references. This paper is part of the Polarization and Conflict Project CIT-2-CT-2004-506084 funded by the European Commission-DG Research Sixth Framework Programme.

1 Introduction

Rather invariably across a large cross-section of countries and time periods income and wealth distributions are skewed to the right and display a heavy upper tail (slowly declining top wealth shares). These observations have lead Vilfredo Pareto, in the *Cours d'Economie Politique* (1897), to introduce the distributions which take his name¹ and to theorize about the possible economic and sociological factors generating wealth distributions of such form. The results of Pareto's investigations take the form of the "Pareto's Law," enunciated e.g., by Samuelson (1965) as follows:

In all places and all times, the distribution of income remains the same. Neither institutional change nor egalitarian taxation can alter this fundamental constant of social sciences.

Since Pareto, economists have lost confidence in "fundamental constant(s) of social sciences".² Nonetheless distributions of income and wealth which are very concentrated and skewed to the right have been well documented over time and across countries. For example, Atkinson (2001), Moriguchi-Saez (2005), Piketty (2001), Piketty-Saez (2003), and Saez-Veall (2003) document skewed distributions of income with relatively large top shares consistently over the last century, respectively, in the U.K., Japan, France, the U.S., and Canada. Large top wealth shares in the U.S. since the 60's are documented e.g., by Wolff (1987, 2004).³ Also, heavy upper tails (power law behavior) of the distributions of income and wealth is a well documented empirical regularity; see e.g., Nirei-Souma (2004) for income in the U.S. and Japan from 1960 to 1999, Clementi-Gallegati (2004) for Italy from 1977 to 2002, and Dagsvik-Vatne (1999) for Norway in 1998.

While Pareto was skeptical that "egalitarian taxation" could have any significant effect on the distribution of income, many have later concluded that the redistributive taxation regimes introduced after World War II did in fact significantly reduce income and wealth inequality; notably, e.g., Lampman (1962) and Kuznets (1955). Most recently, Piketty (2001) has argued that redistributive taxation may have prevented large

¹Pareto distributions are power laws. They display heavy tails, in the sense that the frequency of events in the tails of the distribution declines more slowly than e.g., in a Normal distribution. They represent a subset of the class of stable Levy distributions, that is, of the distributions which are obtained from the version of the Central Limit Theorem which does not impose finite mean and variance; see e.g., Nolan (2005).

²See Chipman (1976) for a discussion on the controversy between Pareto and Pigou regarding the interpretation of the Law. To be fair to Pareto, his view is not necessarily that fiscal policies cannot alter the distribution of wealth, but that fiscal policy is determined by the controlling elites who use it to skew the distribution to their advantage; see Pareto (1900).

³While income and wealth are correlated and have qualitatively similar distributions, wealth tends to be more concentrated than income. For instance the Gini coefficient of the distribution of wealth in the U.S. in 1992 is .78, while it is only .57 for the distribution of income (Diaz Gimenez-Quadrini-Rios Rull, 1997); see also Feenberg-Poterba (2000).

income shares from recovering after the shocks that they experienced during World War II in France.⁴

In this paper we study theoretically the dynamics of the distribution of wealth in an Overlapping Generations economy with bequest and various forms of redistributive taxation. We characterize the transitional dynamics of the wealth distribution as well as the stationary distribution. More specifically, our economy is populated by a continuum of age structured overlapping generations of agents with a constant probability of death as in Blanchard (1985) and Yaari (1965). The population is stationary and each agent who dies is substituted by his/her child. A fraction of the agents are altruistic towards their children and optimally choose the amount of bequests they leave. Agents are born with an initial wealth composed of the bequests of their parents (for those born from parents with preferences for bequests) and, if they qualify, welfare subsidies from the government. Agents face a constant interest rate. They choose an optimal consumption-savings plan, and the allocation of their wealth between annuities and assets which are bequeathed at their death. The government taxes capital income and estates to redistribute wealth in the form of welfare subsidies. The government budget is balanced.

While this economy is very stylized, the stationary distribution of wealth we obtain has the main qualitative properties which characterize wealth distributions: skewedness and fat tails. We show that the stationary wealth distribution is a power law, a Pareto distribution in particular. The two critical ingredients that drive the Pareto wealth distribution in our model are *i*) the accumulation of wealth with age, and more importantly, through inheritance, and *ii*) the redistribution of wealth to the young poor through estate and capital taxes.⁵ The level of wealth concentration and inequality at the stationary distribution depends on the demographic characteristics of the economy, its structural parameters, and on the endogenous growth rate of the economy. More specifically, wealth is less concentrated (the Gini coefficient is lower) the lower is the growth rate of individual wealth accumulation and the higher is the growth rate of aggregate wealth.

Most importantly, the explicit characterization of the stationary distribution of wealth allows us to study analytically the dependence of wealth inequality on various redistributive fiscal policy instruments, like for example capital income taxes, estate taxes, and the form and extent of welfare subsidies. In particular, wealth is less concentrated (the Gini coefficient is lower) for higher capital income taxes and estate taxes. Furthermore, we show that the marginal effect of capital income taxes is much stronger than the effect

⁴This line of argument has been extended to the U.S., Japan, and Canada, respectively, by Piketty-Saez (2003) and Moriguchi-Saez (2005), Saez-Veall (2003).

⁵The importance of intergenerational transfers in accounting for wealth accumulation is emphasized by Kotlikoff and Summers (1981). They argue that intergenerational wealth transfers, rather than life cycle earnings, account for up to 80% of wealth accumulation. See also Gale and Scholtz (1994) for related findings.

of estate taxes.

Finally, we characterize optimal redistributive taxes with respect to a utilitarian social welfare measure. We show that, even with such an "egalitarian" welfare measure, maximizing social welfare is not equivalent to minimizing the concentration or inequality of wealth. This is because minimizing wealth inequality would require an excessive (and hence inefficient) reduction in the economy's growth rate. Most interestingly we find that social welfare is maximized with zero estate taxes. Social welfare maximizing capital income taxes, on the contrary, are positive and, in the simulations we have run, close to the value which minimizes the Gini coefficient.

1.1 Related literature

A large and diverse theoretical literature on the dynamics of individual wealth dating back to the 1950s obtains distributions exhibiting power laws and, in particular, Pareto distributions. Notably, Champernowne (1953), Rutherford (1955), Simon (1955), Wold-Whittle (1957) and most of the subsequent literature study accumulation models in which the postulated stochastic processes drive wealth accumulation differentially for low and high wealth ranges. Typically in these models the stochastic processes are such that there is a lower a reflective barrier to wealth, with lower wealth levels replenished through births, and the levels of wealth above the lowest thinned out by death, or by negative expected growth.⁶ Wold-Whittle (1957) in particular study a birth and death process with population growth, exogenous exponential wealth accumulation, and bequests. Mandelbrot (1960) introduces more general power laws and studies stochastic processes to obtain Pareto-Levy distributions.⁷

The characteristic feature of this literature is that the stochastic processes which generate power laws are essentially exogenous.⁸ In particular they are not the result

⁶In particular Champernowne (1953), and Kalecki (1945) who constructs a log-normal asymptotic distribution, assume negative growth for high levels of wealth.

⁷See also Reed-Jorgensen (2003) for Double Pareto-Lognormal distributions. Most recently, the analysis of stochastic processes generating power laws in the distribution of wealth has become an important subject in Econophysics (see Mantegna-Stanley, 2000, Gabaix-Gopikrishnan-Plerou-Stanley 2003). Many such processes, often along the lines of the cited pioneering studies of the 50's, have been analyzed in this literature. For instance, Nirei-Souma (2004) study multiplicative wealth accumulation models with stochastic rates of return and a reflective lower barrier (Kesten processes); Levy (2003) studies the implications of differential rate of return across groups; Solomon (1999) and Malcai et. al. (2002) study similar processes in which the rate of return on wealth accumulation is interdependent across different groups of individuals (Generalized Lotka-Volterra models); Levy (2003) shows that different rates of return across non-interdependent groups generate wealth distributions which are Pareto only in the tail. Also, Das-Yargaladda (2003) and Fujihara-Ohtsuki-Yamamoto (2004) study stochastic processes in which individuals randomly interact and exchange wealth, and Souma-Fujiwara-Aoyama (2001) add network effects to such random interactions.

⁸Relatedly, an important literature has developed from the early contribution of Simon-Bonini (1958)

of agents' optimal consumption-savings decisions and hence they are not related to the deep structural parameters of the economy nor to any policy parameter of interest. It is then impossible in the context of these models to study for instance the dependence of the distribution of wealth on fiscal policy. A specific fiscal policy in fact affects the distribution of wealth in equilibrium not only through its direct redistributive effects, but also through its indirect effect on the economy's aggregate growth rate, the rate of accumulation of private savings, and through its effect on other fiscal policies induced by government budget balance.

Several previous studies of the distribution of wealth in equilibrium economies with optimizing agents and a well-defined government sector responsible for fiscal policies are based on calibrations and simulations of the distribution of income or earnings. The specific quantitative properties of the distribution of wealth may of course be closely related to the underlying assumed distribution and skewness of earnings. Some studies also exploit different elements of persistent heterogeneity in preferences in addition to a skewed distribution of earnings. For instance, Krusell and Smith (1998) match the skewness of the US wealth distribution in a dynastic model by introducing persistent heterogeneity in the discount factors of the dynasties. Becker and Tomes (1979) generate skewness in income distribution by introducing heterogeneity in the "propensity to invest in children." More recently assortative matching of attributes have also been exploited to obtain or exacerbate the skewness of the distribution of wealth, along the lines of Mandelbrot (1962), Becker (1973), and also Lucas (1978). Quadrini (2000), for example, calibrates the earning distribution to match the skewness of the US wealth distribution, and adopts an assortative matching model to capture the role of entrepreneurship in a dynastic model with imperfect credit markets; see also Cagetti-De Nardi (2000, 2003) for a similar approach. Hughett (1996) uses an OLG model and an exogenous log normal distribution of labor endowments within cohorts that matches the U.S. Gini coefficient for wealth but not the fat tails of the distribution. Laitner (2001) generates various degrees wealth dispersion as measured by the Gini coefficient in an OLG model with a log-normal distribution of earnings and with only a fraction of households that have a bequest motive. De Nardi (2004) on the other hand exploits an explicit non-homogeneous bequest function in an OLG model to match the concentration of wealth in US data. With the intended bequest motive she is able to match the magnitudes of intergenerational wealth transfer ratios, as first suggested by Kotlikoff and Summers (1981) and refined by Gale and Scholtz (1994). Finally, Castaneda-Diaz Gimenez-Rios Rull (2003) calibrate a persistent stochastic process with a highly skewed distribution of skills, and hence earnings, in a model where agents have constant probabilities of retirement and death, and, due to the lack of annuity markets, leave accidental bequests. They quantitatively

who adopt similar methods to study the statistical properties of the distribution of firms by size. Recently, in this context, Luttmer (2004, 2005) has obtained power laws by the explicit modeling of the entry and exit decisions of firms.

account for the U.S. wealth distribution and Gini coefficient.⁹ A highly informative survey of the recent literature is given by De Nardi and Cagetti (2005).

2 Wealth accumulation in an OLG economy with bequests

Consider the Overlapping Generation (OLG) economy in Yaari (1965) and Blanchard (1985).¹⁰ Each agent at time t has a probability of death $\pi(t) = pe^{-pt}$.¹¹ Let $c(s, t)$ and $w(s, t)$ denote, respectively, consumption and wealth at t of an agent born at s . All agents have identical momentary utility from consumption $u(c(s, t))$ satisfying the standard monotonicity and concavity assumptions. Agents may care about the bequest they leave to their children. We assume for simplicity that agents have a single heir. At any time t an agent allocates his wealth between an asset and an annuity. The asset pays a return r , gross of taxes. We assume r is an exogenous constant (productivity) parameter. In perfect capital markets, by no-arbitrage, the annuity pays a return $p + r$, where p is the probability of death. Let $\omega(s, t)$ denote the amount invested in the asset at time t by an agent born at s , with wealth $w(s, t)$. Therefore $w(s, t) - \omega(s, t)$ denotes the amount that an agent invests in the annuity. If the agent dies at time t the amount bequeathed is $\omega(s, t)$. Letting b denote the estate tax, the agent's heir inherits $(1 - b)\omega(s, t)$. We also abstract away from labor earnings: this is a shortcoming of our model that we adopt for the sake of simple analytic solutions.¹²

A fraction of the agents are altruistic towards their children. For expository reasons we assume "joy of giving" preferences for bequests: the agent's utility from bequests is $\phi((1 - b)\omega(s, t))$, where ϕ denotes an increasing bequest function.¹³ At the end of this Section we discuss how our analysis can be extended without loss of generality to the standard case in which parents internalize their children's utility. A subset of agents have no preferences for bequests, that is, they have $\chi = 0$. An agent born at time s receives, at birth, initial wealth $w(s, s)$ (and, again for simplicity, no labor income). We

⁹Another mechanism which produces skewed distributions of earnings proposed by Roy (1950) is the multiplicative composition of several randomly distributed factors (e.g., talent attributes) which gives rise to a log-normal distribution of wealth. We should also note that Mincer (1958) derives a log-normal distribution of earnings from a simple human capital choice model.

¹⁰More specifically, we consider the formulation with endogenous bequests in Yaari (1965).

¹¹Therefore, an agent lives t periods with probability $\int_t^\infty pe^{-pt} dt = e^{-pt}$, and his expected life at any time t is $\int_t^\infty (s - t) pe^{-(s-t)p} ds = p^{-1}$.

¹²As will be shown below and also follows from the Blanchard model, (see equation (8)), the growth rate of an agent's wealth and that of the economy-wide wealth are not equal. Introducing labor earnings growing at the rate of economy-wide capital would introduce a non-stationarity into the agent's decision problem and create aggregation problems for the viability of simple analytic solutions.

¹³Note that we assume that parents correctly anticipate that bequests are taxed and this reduces accordingly their "joy of giving."

let τ denote the capital income tax¹⁴.

The maximization problem of an agent born at time s involves choosing consumption and bequests paths, c, ω to maximize

$$\int_t^\infty e^{(\theta+p)(t-v)} (u(c(s, v)) + p\phi((1-b)\omega(s, v))) dv \quad (1)$$

subject to:

$$w(s, t) = w(s, s) + \int_s^t ((r + p - \tau)w(s, v) - p\omega(s, v) - c(s, v)) dv \quad (2)$$

In the interest of closed form solutions we assume

$$u(c) = \ln(c), \quad \phi(\omega) = \chi \ln \omega$$

The characterization of the optimal consumption-savings path is then straightforward.¹⁵

Proposition 1 *The consumption-savings path which solves the agent's maximization problem (1) is characterized by:*

$$c = \eta w, \quad \omega = \chi \eta w, \quad (3)$$

with $\eta = \frac{(p+\theta)}{p\chi+1}$; and

$$\dot{w}(s, t) = (r - \theta - \tau)w(s, t) \quad (4)$$

Notably, the growth rate of an agent's wealth, $g = r - \theta - \tau$, is independent of the preference parameter for bequests χ . Agents who care about leaving bequests to their children consume a smaller fraction of wealth than agents who do not (and invest all their wealth in annuities), but grow at the same rate g . As a consequence, g decreases with the capital income tax τ but is independent of estate taxes b .

While we have solved for the agents' consumption-savings problem under the assumption of "joy of giving" preferences for bequests, the same analysis can be extended to the case of altruistic preferences. Consider to this effect the case of an agent who values his son's utility $\alpha \leq 1$,¹⁶ whose maximization problem in recursive form is:

¹⁴We assume for simplicity that the tax τ is imposed on both the asset and the annuity.

¹⁵We restrict parameters so that interior solutions obtain. The agent's choice must also satisfy the Transversality condition,

$$0 = \lim_{v \rightarrow \infty} e^{-\int_t^v r+p} w(s, v) dv.$$

We assume however $r > -p$ to guarantee that the Transversality condition is satisfied.

¹⁶Note that our formulation is different from that of Phelps-Pollak (1968) inasmuch as it induces a time-consistent preference ordering over consumption sequences even for $\alpha < 1$.

$$V(w(s, t)) = \max_{c, \omega} \int_t^\infty e^{(\theta+p)(t-v)} (\ln c(s, v) + p\alpha V(\omega(s, v))) dv$$

subject to

$$\frac{dw(s, t)}{dt} = (r + p)w(s, t) - p\omega - c(s, t)$$

and the Transversality condition. We show in Appendix A that optimal consumption-savings decision of an altruistic agents correspond to those of an agent with "joy of giving" preferences with endogenous preference for bequest $\chi = \frac{1}{\theta+p(1-\alpha)}$. Therefore, in the case of altruistic preferences,

$$c = (\theta + p(1 - \alpha))w, \quad \omega = \alpha w$$

and

$$\dot{w}(s, t) = (r - \theta - \tau)w(s, t)$$

Note that, when $\alpha = 1$ and the parent cares about his son as for himself all of the wealth is deposited in the bequest account.

2.1 The aggregate economy

We assume that the population is constant, and normalized to 1. As a consequence, for any agent who dies at any time there is a new agent born. Since each agent in the economy dies with probability p , at any time s , p agents die.¹⁷

Let the aggregate economy's growth rate be denoted g' . Aggregate wealth is defined as:

$$W(t) = \int_{-\infty}^t w(s, t)pe^{p(s-t)} ds$$

Let $W(s, t)$ denote the aggregate wealth at time t of all agents born at time s . Then

$$\dot{W}(t) = W(t, t) - pW(t) + \int_{-\infty}^t \frac{dW(s, t)}{dt} pe^{p(s-t)} ds$$

Since the growth rate of wealth is constant across all agents in our economy, $\frac{dW(s, t)}{dt} = (r - \tau - \theta)W(s, t)$ and

$$\dot{W}(t) = W(t, t) - pW(t) + (r - \tau - \theta)W(t) \tag{5}$$

The growth rate of $W(t)$ is determined once we specify the initial wealth of all newborn agents at each time t , $W(t, t)$. In our economy the distribution of initial wealth

¹⁷At any time t the size of the cohort born at 0 is pe^{-pt} . The total population of the economy, at any time t is therefore 1: $\int_{-\infty}^t pe^{(s-t)p} ds = e^{(s-t)p} \Big|_{-\infty}^t = 1$.

$w(t, t)$ across agents is determined by *i*) any component of wealth that is inherited in addition to the financial wealth inherited from parents, for example, some component of human capital, and *ii*) wealth subsidies due to the government welfare policy, notably fiscal subsidies to support a minimal wealth at birth. For simplicity and without loss of generality we assume that no initial human capital component is present. Instead, in the next Section, we study different welfare policies.

Independently of the specific welfare policies however, the aggregate wealth of newborns at t , $W(t, t)$, is determined once the demographics of the economy are specified if, as postulated, the government simply balances the budget. Regarding the demographics we assume that, of the p agents dying at any s , only $q < p$ leave an inheritance, while $p - q$ die with no estate, e.g., because they have no preferences for bequests, $\chi = 0$.¹⁸ Correspondingly, $p - q$ agents are born with no wealth and q with the inherited wealth.

Let the fraction of wealth invested in annuity be denoted μ . The fraction of assets carried by an agent as a fraction of total assets, and inherited upon death, is then denoted by $1 - \mu$ and, from (3), it can be written as:

$$1 - \mu = \frac{\omega}{w} = \frac{(p + \theta) \chi}{p\chi + 1}; \quad (6)$$

As a consequence the aggregate wealth of newborn at t is comprised of the aggregate inherited wealth, $q(1 - \mu)(1 - b)W(t)$ and of the aggregate tax receipts which are re-distributed, $q(1 - \mu)bW(t) + \tau W(t)$, that is,

$$W(t, t) = (q(1 - \mu) + \tau)W(t)$$

The dynamics of aggregate wealth then is

$$\dot{W}(t) = (r - \tau - \theta - p)W(t) + q(1 - \mu)(1 - b)W(t) + \tau W(t)$$

and

$$g' = r - \theta - p + q(1 - \mu) \quad (7)$$

It follows from (6) that μ is independent of estate and capital income taxes. Capital income taxes however depress the savings rate by reducing the net interest rate on savings. It will be important in the following to restrict parameters so that individual wealth accumulates faster than aggregate wealth, that is:

$$g - g' = p - q(1 - \mu) - \tau > 0 \quad (8)$$

We note however that we may also allow some of the tax collections to finance exogenous government expenditures or a public good that enters the preferences of agents separably

¹⁸In other words, a fraction $\frac{p-q}{p}$ of the agents have no preferences for bequests.

without influencing other decisions. If only a fraction $\varphi < 1$ of capital taxes are redistributed, then we have $g' = r - \theta - p + q(1 - \mu) - (1 - \varphi)\tau$ and $g - g' = p - q(1 - \mu) - \varphi\tau > 0$. If $\varphi < 1$, the upper bound on capital taxes would be higher without violating the non-negativity of $g - g'$.¹⁹

2.2 Welfare policy

The growth rate of aggregate wealth, g' , does not depend on the specifics of the welfare policy, but only on the proportion of wealth distributed as subsidies in the aggregate.²⁰ The distribution of wealth, on the other hand, does depend on the welfare policy. We shall study two main welfare policies which are distinct in terms of their redistributive means. Both policies guarantee that all agents born at any time t with no inheritance receive a transfer of wealth to bring them to a minimum wealth level $\underline{w}(t)$ which grows at the aggregate economy's rate g' , that is $\underline{w}(t) = \underline{w}e^{g't}$. The two welfare policies differ instead on how they support the wealth of agents born with an inheritance:

Lump-sum subsidies. All agents born at any t with an inheritance receive a lump-sum subsidy equal to $x(t)$ which grows at the aggregate economy's rate g' : $x(t) = xe^{g't}$.²¹

Means-tested subsidies. All agents born at any t with inheritance less than $\underline{w}(t)$ get a transfer of wealth to bring them to $\underline{w}(t)$.

In the case of lump-sum subsidies, the total amount of subsidies paid by the government at any time t is independent of the distribution of wealth at t and is a constant fraction of wealth at each time t :

$$(p - q)\underline{w} + qx$$

A fiscal policy (τ, b) determines the set of feasible welfare policies (\underline{w}, x) , which satisfies

$$(p - q)\underline{w}(t) + qx(t) = \tau W(t) + qb(1 - \mu)W(t)$$

¹⁹We could also require only a fraction of estate taxes to be redistributed, in which case b would also enter into the determination of $g - g'$.

²⁰Note that we have assumed that welfare policies are not anticipated by the parents in their bequest decisions. We require this assumption in order to guarantee that the growth rate of individual wealth is constant, which is in turn necessary for the linearity of the Partial Differential Equation governing the dynamics of the distribution of wealth; see footnote 22.

²¹We assume for simplicity that

$$(1 - \mu)(1 - b)\underline{w}(t) + x(t) \geq \underline{w} \tag{9}$$

so that no inheriting agent has initial wealth smaller than the minimal wealth.

In the case of means-tested subsidies the total amount of subsidies paid by the government at any time t depends on the distribution of wealth at t . In particular, the policy subsidizes the wealth of those newborn whose parents are relatively poor at death, that is, have wealth between $\underline{w}(t)$ and $((1-b)(1-\mu))^{-1}\underline{w}(t)$. Let $f(w, t)$ denote the distribution of wealth at time t . Total subsidies (government expenditures) at time t are:

$$(p-q)\underline{w}(t) + q \int_{\underline{w}(t)}^{((1-b)(1-\mu))^{-1}\underline{w}(t)} (\underline{w}(t) - (1-b)(1-\mu)w) f(w, t) dw \quad (10)$$

It is important to note that such subsidies can be supported by a stationary tax policy (with constant rates τ , b , as we have assumed) only if the distribution of wealth is stationary (independent of t) or if we allow the government to run fiscal deficits and surpluses and only require a balanced budget intertemporally, rather than for all t .²²

3 The distribution of wealth in the OLG economy

We study the dynamics of the distribution of wealth of the OLG economy with inheritance and estate taxes introduced in the previous section. We solve for both the transitional dynamics and the stationary distribution. We study conditions under which the stationary distribution is Pareto.²³

Let the distribution of wealth at time t be denoted $f(w, t)$. Its dynamics are described by a linear partial differential equation (PDE) with variable coefficients, an initial condition for the initial wealth distribution, and a boundary condition that reflects the injection of wealth to newborns under our welfare policies.

Let $\sigma(w)$ denote the wealth a parent needs to have at time of death t for his heir born at $t + \Delta$ to inherit wealth w . The expression $\sigma(w)$, linear and increasing in w , takes

²²Recall that we have assumed that agents value net bequests, $(1-b)(1-\mu)w$. Importantly, they do not value the subsidies received by their children through the welfare state. This is just for analytical tractability so that μ remains constant for all wealth levels. An alternative numerically tractable formulation for the utility of bequests under means-tested subsidies could be $\chi \max\{0, \ln\left((1-b)(1-\mu)\frac{w}{\underline{w}}\right)\}$, which guarantees that agents will not give any bequests if they die with discounted wealth smaller than $((1-b)(1-\mu))^{-1}\underline{w}$. For lump-sum subsidies, where all agents receive x at birth and start life with $w \geq \underline{w}$, the bequest function would be $\ln\left((1-b)(1-\mu)\frac{w+x}{\underline{w}}\right)$. In either case however μ would depend on wealth.

²³Wold-Whittle (1957) pioneered the methods of analysis of the dynamics of the distribution of wealth that we adopt in this paper. They studied an economy with dual accumulation. Below a cut-off wealth is assumed to simply grow exponentially. The distribution of wealth above the cut-off is instead determined by a birth-death process. While Wold-Whittle (1955) assume full inheritance and do not study any fiscal policies, population growth in their economy dilutes wealth across children and hence its effect are related to the effects of partial inheritance and estate taxes in our economy.

a different form for the two specification of welfare policies that we study.²⁴ At time 0 the distribution of wealth $w \in (\underline{w}, \infty)$ is exogenous. Let it be denoted $h(w)$. We assume for simplicity that at time $t = 0$ all agents have wealth greater than minimal wealth:

$$h(w) = 0 \text{ for any } w \leq \underline{w}$$

The PDE describing the evolution of the distribution of wealth is obtained as the Chapman-Kolmogorov equation which governs the dynamics of $f(w, t)$ (its derivation is detailed in Appendix A):

$$\frac{\partial f(w, t)}{\partial t} = -(p + g) f(w, t) + q \frac{\partial \sigma(w)}{\partial w} f(\sigma(w), t) - gw \frac{\partial f(w, t)}{\partial w} \quad (11)$$

with initial condition is

$$f(w, 0) = h(w) \quad (12)$$

The distribution of wealth at time t must also satisfy the boundary condition (derived in Appendix A):

$$f(\underline{w}(t), t) = \frac{p - q}{g} \frac{1}{\underline{w}(t)} + \frac{1}{g} \frac{1}{\underline{w}(t)} q \int_{\underline{w}(t)}^{\sigma(\underline{w}(t))} f(w, t) dw \quad (13)$$

This boundary condition guarantees that, at each t , the population size is constant and normalized to 1; that is, $\int f(w, t) dw = 1$. Note that $f(\underline{w}(t), t)$, the density of wealth at $w = \underline{w}(t)$, is composed of the density of wealth corresponding to the $p - q$ agents who do not receive any inheritance, $\frac{p - q}{g} \frac{1}{\underline{w}(t)}$, and of the agents whose inheritance at t is below $\underline{w}(t)$, $\frac{1}{g} \frac{1}{\underline{w}(t)} q \int_{\underline{w}(t)}^{\sigma(\underline{w}(t))} f(w, t) dw$. Recall that under our assumptions this last component is positive only with a welfare policy characterized by means-tested subsidies, and is zero with lump-sum subsidies.

Formally, our problem is the following: Find a density $f(w, t)$ which satisfies the PDE (11) for all $w > \underline{w}(t)$, the initial condition (12), and the boundary condition (13). It will, however, be much more convenient to work in variables discounted by the aggregate economy's growth rate g' . For this purpose define $z = we^{-g't}$. Note that the support of z is stationary and equal to (\underline{w}, ∞) . The PDE which we obtain after the necessary

²⁴With lump-sum subsidies

$$\sigma(w(t)) = \frac{w(t) - xe^{g't}}{(1 - \mu)(1 - b)};$$

while with means-tested subsidies

$$\sigma(w(t)) = \frac{w(t)}{(1 - \mu)(1 - b)}.$$

transformations is:

$$\frac{\partial f(z, t)}{\partial t} = -(p + g - g') f(z, t) + q \frac{\partial \sigma(z)}{\partial z} f(\sigma(z), t) - (g - g') z \frac{\partial f(z, t)}{\partial w} \quad (14)$$

with initial condition:

$$f(z, 0) = h(z) \quad (15)$$

and boundary condition:

$$f(\underline{w}, t) = \frac{p - q}{g - g'} \frac{1}{\underline{w}} + \frac{1}{g - g'} \frac{1}{\underline{w}} q \int_{\underline{w}}^{\sigma(\underline{w})} f(z, t) dz \quad (16)$$

To solve (11) under (15) and (16) we apply the "method of characteristics" as detailed in Appendix C.

Lemma 1 *There exists a distribution of discounted wealth $f(z, t)$ which satisfies (14) as well as (15). It is characterized by:*

$$f(z, t) = \begin{cases} \left(\frac{z}{\underline{w}} \right)^{-\frac{p}{g-g'}-1} f(\underline{w}, t - \tau(z, \underline{w})) + \\ \quad + q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y), t - \tau(z, y)) (y)^{\left(\frac{p}{g-g'}\right)} (g - g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy & \text{for } z \in (\underline{w}, \underline{w}e^{(g-g')t}) \\ e^{-(p+g-g')t} h(z e^{(g-g')t}) \\ \quad + q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y), t - \tau(z, y)) (y)^{\left(\frac{p}{g-g'}\right)} (g - g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy & \text{for } z \geq \underline{w}e^{(g-g')t} \end{cases} \quad (17)$$

where $\tau(z, y) = \frac{\ln z}{\ln y} \frac{1}{g-g'}$

Proof. See Appendix D. ■

This characterization has an interesting economic interpretation. Notice that $\tau(z, y) = \frac{\ln z}{\ln y} \frac{1}{g-g'}$ represents the age of an agent who has wealth z at time t and was born with wealth y . The age of an agent who has wealth z at time t and was born with wealth \underline{w} is then $\tau(z, \underline{w})$. Consider the density of any discounted wealth level $z \in (\underline{w}, \underline{w}e^{(g-g')t})$.

The first component of the density $f(z, t)$ in (17) is $\left(\frac{z}{\underline{w}}\right)^{-\frac{p}{g-g'}-1} f(\underline{w}, t - \tau(z, \underline{w}))$. It represents the density of agents who have entered the economy with wealth \underline{w} , have never died since, and have reached wealth z at t . It is determined by the boundary condition at time $t - \tau(z, \underline{w})$. Similarly, the second component of the density $f(z, t)$ in (17) is $q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y), t - \tau(z, y)) (y)^{\left(\frac{p}{g-g'}\right)} (g - g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy$. It represents the density of agents who have entered the economy with some wealth y , have never

died since, and have reached wealth z at t . Consider instead the density of discounted wealth levels z at time t greater than $\underline{w}e^{(g-g')t}$. The only agents who can possess such a discounted wealth level are: *i*) those agents who were born at time 0 and have never died, *ii*) the children of those agents who have died at some time $t' < t$ and left inheritance larger than $\underline{w}e^{(g-g')t'}$. The density of these agents is represented by the second line of (17).

The distribution of wealth $f(z, t)$ must then satisfy (17) as well as (16). It is in general impossible to find a closed form solution unless the boundary condition (16) has the property that $f(\underline{w}, t)$ is constant in t , which in fact is the case if no agent leaves any inheritance. We will discuss this as a special case in Section 3.

We can nonetheless study the limit distribution of the dynamics of $f(z, t)$. First of all we can show that (see the proof of Proposition 2 in Appendix A) the density of discounted wealth levels z at time t greater than $\underline{w}e^{(g-g')t}$, represented by the second line of (17), declines with time. It is in fact bounded above by $e^{-(p-q+g-g')t} h(z e^{-(g-g')t})$. It therefore declines at a rate (greater than) $p - q + g - g'$, due to the rate $p - q$ at which agents die with no inheritance and the rate at which the density "spreads" on account of growth, $g - g'$.

Proposition 2 *The distribution of wealth $f(z, t)$ which satisfies (17) as well as (16) has a stationary distribution, $f(z)$, which solves the following integral equation:*

$$f(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) + q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y)) (y)^{\left(\frac{p}{g-g'}\right)} (g-g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy \quad (18)$$

for

$$f(\underline{w}) = \frac{p-q}{g-g'} \frac{1}{\underline{w}} + \frac{1}{g-g'} \frac{1}{\underline{w}} q \int_{\underline{w}}^{\sigma(\underline{w})} f(z) dz. \quad (19)$$

The integral equation (18) can be solved for quite generally. To provide intuition, we proceed by studying various special cases first.

No inheritance We first study the special case in which agents have no preferences for bequests, $\chi = 0$. In this case agents only invest in annuities and leave no bequests, $\mu = 1$. All p newborns at time t receive \underline{w} ($q = 0$). Furthermore, from (8), $g - g' = p - \tau$. In this economy, the density of wealth at the boundary \underline{w} is constant over time and the boundary condition is reduced to:

$$f(\underline{w}, t) = \frac{p}{g-g'} \frac{1}{\underline{w}} = \frac{p-q}{p-\tau} \frac{1}{\underline{w}} \quad (20)$$

while the initial condition is the same as in (15).

Proposition 3 *The economy without bequests has the following distribution of discounted wealth at each time t :*

$$f(z, t) = \begin{cases} \frac{p}{p-\tau} \underline{w}^{\frac{p}{p-\tau}} z^{-\left(\frac{p}{p-\tau}+1\right)} & \text{for } z \in (\underline{w}, \underline{w}e^{(p-\tau)t}) \\ e^{-(p+(p-\tau))t} h(z e^{-(p-\tau)t}) & \text{for } z \geq \underline{w}e^{(p-\tau)t} \end{cases} \quad (21)$$

$f(z, t)$ is a truncated Pareto distribution in the range $(\underline{w}, \underline{w}e^{(p-\tau)t})$. The ergodic distribution of discounted wealth is

$$f(z) = \frac{p}{p-\tau} \underline{w}^{\frac{p}{p-\tau}} z^{-\left(\frac{p}{p-\tau}+1\right)}$$

which is a Pareto distribution with finite mean.²⁵

Full inheritance, no estate taxes We now study another special case, in which agents leave all of their wealth as inheritance to their heirs and no estate taxes are imposed. This requires that χ be large enough and $b = 0$. Recall however that at each time t , nonetheless, $p - q$ agents die without heirs and $p - q$ agents are born with minimal wealth \underline{w} . Furthermore, from (8), $g - g' = p - q - \tau$. If $\mu = 0$, $x = 0$, it follows immediately that the boundary condition (16) requires:

$$f(\underline{w}, t) = \frac{p - q}{g - g'} \frac{1}{\underline{w}}$$

with the initial condition

Proposition 4 *The economy with full inheritance and no estate taxes has the following distribution of discounted wealth at each time t :*

$$f(z, t) = \begin{cases} \frac{p-q}{p-q-\tau} \underline{w}^{\frac{p-q}{p-q-\tau}} z^{-\left(\frac{p-q}{p-q-\tau}+1\right)} & \text{for } z \in (\underline{w}, \underline{w}e^{(p-q-\tau)t}) \\ e^{-(p+(p-\tau))t} h(z e^{-(p-q-\tau)t}) & \text{for } z \geq \underline{w}e^{(p-q-\tau)t} \end{cases} \quad (22)$$

It is a truncated Pareto distribution in the range $(\underline{w}, \underline{w}e^{(p-q-\tau)t})$. The ergodic distribution of discounted wealth is

$$f(z) = \frac{p - q}{p - q - \tau} \underline{w}^{\frac{p-q}{p-q-\tau}} z^{-\left(\frac{p-q}{p-q-\tau}+1\right)}$$

which is a Pareto distribution with finite mean.²⁶

Note that in fact this economy is observationally equivalent to an economy without bequest in which all agents die without heirs with probability $p - q$. (The fraction q of agents who die at any t leaving full inheritance to the offspring effectively do not die).

²⁵The mean is finite since $\frac{p}{p-\tau} > 1$.

²⁶The mean is finite since $\frac{p-q}{p-q-\tau} > 1$.

Means-tested subsidies We are now ready to study the case in which agents leave part of their wealth as inheritance to their heirs and estate taxes are imposed; that is, the case in which $0 < \mu, b < 1$. We first study the economy in which welfare policies are characterized by means-tested subsidies.

We study directly the stationary distribution as in this case we cannot analytically solve (17) for the transitional dynamics of $f(z, t)$. We can therefore look for a function $f(z)$ which satisfies the integral equation (18) and the boundary condition (19). For this economy (see footnote 24), we have

$$\sigma(y) = \frac{y}{(1-\mu)(1-b)}$$

We use the transformation $j = \sigma(y) = \frac{y}{(1-\mu)(1-b)}$ and obtain, from (18):

$$f(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) + q(g-g')^{-1} \int \frac{\frac{z}{\underline{w}}(1-b)}{(1-\mu)(1-b)} f(j) \left[((1-\mu)(1-b)j)^{\left(\frac{p}{g-g'}\right)} z^{-\left(\frac{p}{g-g'}+1\right)} \right] dj \quad (23)$$

Recall that, from (8), $g - g' = p - q(1 - \mu) - \tau$. We proceed by guessing a Pareto distribution for $f(z)$:

$$f(z) = \frac{p - aq(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau} \underline{w}^{\frac{p - aq(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau}} z^{-\left(\frac{p - aq(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau} + 1\right)} \quad (24)$$

and then solve for the parameters a to satisfy, respectively, (23) and the boundary condition (19).

After some algebra, we can show that the guess (24) satisfies (23) if and only if a solves the fixed point equation:

$$a = ((1 - \mu)(1 - b))^{\left(\frac{p - aq(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau} - 1\right)} \quad (25)$$

It is straightforward to show that (25) has a unique fixed point, which we denote a^* , and that $0 < a^* < 1$. The boundary condition (19) is also satisfied and $\int_{\underline{w}}^{\infty} f(z) dz = 1$. The quantity $a(1 - \mu)(1 - b) = q((1 - \mu)(1 - b))^{\frac{p - a^*q(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau}}$ is one minus the value of the cumulative Pareto distribution at $\underline{w}((1 - \mu)(1 - b))^{-1}$ and represents the fraction of the q agents that inherit wealth greater than \underline{w} , and receive no subsidies to supplement their wealth at birth.

We summarize this analysis with the following result.

Proposition 5 *The economy with inheritance, estate taxes, and means-tested subsidies has a stationary distribution of discounted wealth*

$$f(z) = \frac{p - a^*q(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau} \underline{w}^{\frac{p - a^*q(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau}} z^{-\left(\frac{p - a^*q(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau} + 1\right)}, \quad (26)$$

for $0 < a^* < 1$ satisfying (25)

which is a Pareto distribution with finite mean.²⁷

We may also characterize the distribution of wealth conditional on age. Let $A(z; n)$ characterize the stationary wealth distribution of those agents who have reached age n . An n year old with current wealth z must have started life with wealth $ze^{-(g-g')n} \geq \underline{w}$. Note that at the stationary distribution of wealth $f(z)$, given by Proposition 5, after allowing for growth, the inflow of the wealth distribution of newborns, exactly offsets the outflow of the wealth distribution of the dying agents, so $f(z)$ remains invariant.

Corollary 6 *The stationary wealth distribution of n year old agents is*

$$A(z; n) = \begin{cases} qf\left(\sigma\left(ze^{-(g-g')n}\right)\right)e^{-pn}, & ze^{-(g-g')n} > \underline{w} \\ f\left(ze^{-(g-g')n}\right)e^{-pn} & ze^{-(g-g')n} = \underline{w} \end{cases}$$

where the density $f(z)$ is given by Proposition 5..

If we take the current time to be 0, the first line on the right represents the number newborns who inherited exactly $ze^{-(g-g')n} > \underline{w}$ at time $-n$ and therefore whose parents had to have $\sigma\left(ze^{-(g-g')n}\right)$. Their current wealth is z . The second line represent those who inherited the amount $ze^{-(g-g')n} = \underline{w}$ or less at time $-n$, and had to have a subsidy greater than or equal to zero to bring them to the boundary \underline{w} . Again, their current wealth is reached z . Note that those coming from the boundary and who had wealth \underline{w} exactly at time $-n$ constitute everyone who then had wealth \underline{w} . However those represented in the first line on the right, who at $-n$ inherited $ze^{-(g-g')n} > \underline{w}$ and whose parents had $\sigma\left(ze^{-(g-g')n}\right) > \underline{w}$, were not the only ones who had wealth $ze^{-(g-g')n}$ at the time. The others were those who had remained alive, grew into wealth $ze^{-(g-g')n}$, and were older than zero years.

Since $f(z)$ is a Pareto distribution on $z \geq \underline{w}$, it follows that $A(z; n)$ is also a Pareto density on $z \geq \underline{w}e^{(g-g')n}$ scaled down by the factor qe^{-pn} . The Corollary above clearly illustrates the role of inheritance rather than age in generating the skewness of the wealth distribution within each age cohort in our economy.

Lump-sum subsidies We now study the economy for which $0 < \mu, b < 1$ where welfare policies support a minimal discounted wealth \underline{w} and provide all agents with discounted wealth greater than or equal to \underline{w} with discounted lump-sum subsidies x . Under our assumptions it follows immediately that the boundary condition (20) holds, that is $f(\underline{w}, t) = \frac{p-q}{g-g'} \frac{1}{\underline{w}}$.

²⁷The mean is finite since $\frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau} > 1$.

The stationary distribution satisfies the integral equation (18). For this economy (see footnote 21), we have

$$\sigma(y) = \frac{y-x}{(1-\mu)(1-b)}, \text{ and hence } \sigma(\underline{w}) = \underline{w}, \quad \frac{\partial \sigma(z)}{\partial z} = \frac{1}{(1-b)(1-\mu)}$$

We operate the transformation $j = \sigma(y) = \frac{y-x}{(1-\mu)(1-b)}$ and obtain, from (18):

$$f(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) + q(g-g')^{-1} \int_{\underline{w}}^{\frac{z-x}{(1-\mu)(1-b)}} f(j) \left[((1-\mu)(1-b)j+x)^{\left(\frac{p}{g-g'}\right)} (z)^{-\left(\frac{p}{g-g'}+1\right)} \right] dj \quad (27)$$

While we do not have of a closed form solution to this integral equation, a unique solution exists (see Appendix D). Moreover we can show that, for large z , the distribution of discounted wealth is approximately Pareto. We summarize the analysis with the following result.

Proposition 7 *The economy with inheritance, estate taxes, and welfare policies with minimal wealth support and lump-sum subsidies has a stationary distribution of discounted wealth with the following properties:*

i) for any z , it is bounded below by a Pareto distribution with exponent

$$\frac{p}{p-q(1-\mu)-\tau} \quad (28)$$

and it is bounded above by a Pareto distribution with exponent

$$\frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau} > 1, \quad \text{for } 0 < a^* < 1 \text{ satisfying (25)}$$

ii) for large z , it is approximated by a Pareto distribution with exponent

$$\frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau} > 1, \quad \text{for } 0 < a^* < 1 \text{ satisfying (25)}$$

3.1 Fiscal Policy Effects

In this section we study the effects fiscal policy changes, that is changes in estate taxes b and capital income taxes τ on the aggregate growth rate of the economy and on the stationary distribution of discounted wealth. Furthermore we characterize optimal redistributive taxes with respect to an utilitarian social welfare measure. We restrict our analysis to welfare policies with means-tested subsidies.

Positive effects of fiscal policies We have shown in the previous section that, without lump-sum transfers, the stationary distribution of discounted wealth is a Pareto distribution with finite mean whose exponent depends on the policy parameters, on the deep preference parameters, on the demographics, and on the interest rate. More specifically, for parameters such that $0 < \mu < 1$ the Pareto exponent of the stationary distribution, denoted by P , is²⁸

$$P = \frac{p - a^*q(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau}, \quad \text{with } a^* = (1 - \mu)^{\left(\frac{p - a^*q(1 - \mu)(1 - b)}{p - q(1 - \mu) - \tau} - 1\right)} \quad (29)$$

For a Pareto distribution the Gini coefficient, the standard measure of inequality, is inversely related to the Pareto exponent. In particular, as noted by Chipman (1974), letting G denote the Gini coefficient,

$$G = \frac{1}{2P - 1}$$

We proceed by characterizing the effects of policy variables $b \in [0, 1]$ and $\tau \in [0, p - q(1 - \mu)]$ on P . The upper bound on τ is required so that $g - g'$, and therefore P , remain non-negative.²⁹

Proposition 8 *The Pareto coefficient of the economy's stationary distribution of discounted wealth is increasing in capital income taxes τ , $\frac{\partial P(\tau, b)}{\partial \tau} > 0$, and non-decreasing in estate taxes b , $\frac{\partial P(\tau, b)}{\partial b} \geq 0$. Perfect equality ($G = 0, P = \infty$) is attained for $\tau = p - q(1 - \mu)$ for any b .*

The effect of taxes on the Pareto coefficient and therefore on inequality operate through several channels. The denominator (29) is in fact $g - g'$. To the extent that capital taxes slow the growth of individual wealth relative to the growth of aggregate wealth, inequality decreases. In addition, estate and capital taxes in the numerator of (29) affect the number of people whose inheritance falls short of minimum wealth and have to be subsidized, both directly and through a^* . Note however that equation (29) for the Pareto coefficient is in implicit form: the number of people whose inheritance falls short of minimum wealth and need to be subsidized itself depends on the distribution, and therefore on the Pareto coefficient. Since a reduction in inequality and a higher Pareto coefficient both reduce the number of people who need be subsidized, the net effect of taxes on inequality is not immediately clear by inspection, but the Proposition above proves that in fact capital and estate taxes reduce inequality.

²⁸Note that $P = \frac{p}{p - \tau}$ if $\mu = 1$, while, if $\mu = 0$, $P = \frac{p - q}{p - q - \tau}$.

²⁹The upper bound on τ is $p - q(1 - \mu)$ under the assumption that all capital taxes are redistributed. If only a fraction φ are redistributed then the upper bound is higher and given by $\varphi^{-1}(p - q(1 - \mu))$. See the last paragraph of section 2.1 above.

To better illustrate the effects of fiscal policies on the Pareto coefficient we calibrate a simple economy. We choose the following parameter values:

$$p = 0.016, q = 0.013, \theta = 0.04, \chi = 10, r = 1.08 \quad (30)$$

We choose p for an expected productive life of $p^{-1} = 62$ years, and $\chi = 10$ implying that agents with a positive bequest motive hold 0.49% of their wealth in inheritable, non-annuitized assets. The fraction of the population that leave bequests to their heirs is $\frac{q}{p} = 0.8125$. Figure 1, shows the the relationship between P and the taxes (b, τ) .

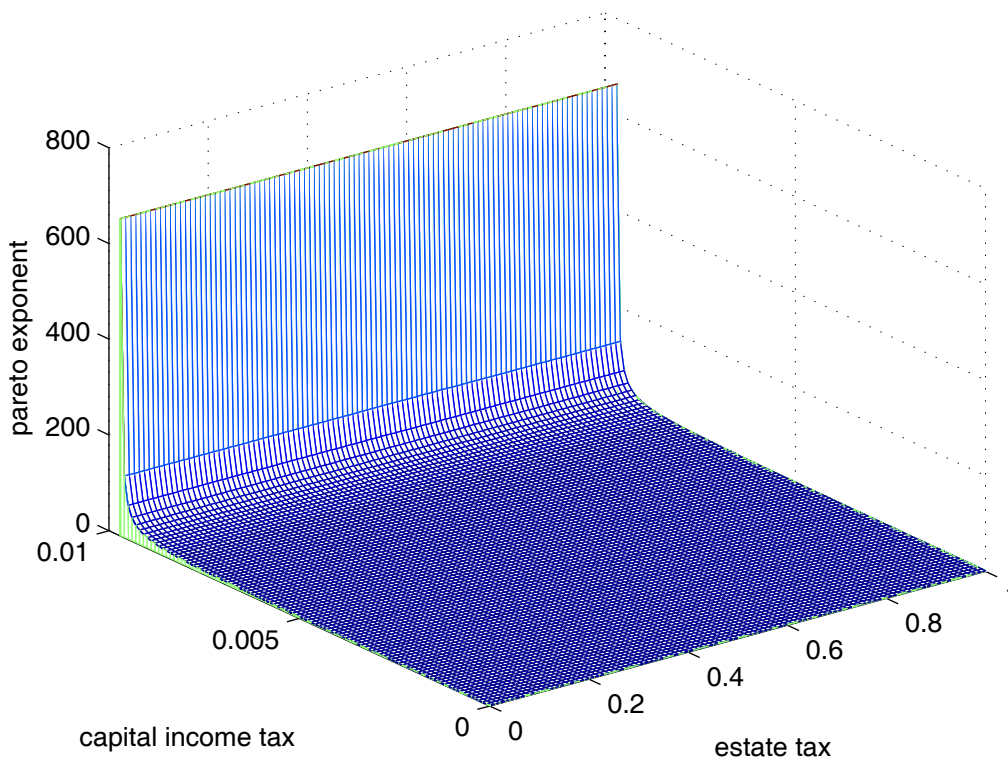


Figure 1:

The effect of capital income taxes on P is essentially due to their effect on the differential growth rate $g - g' = p - q(1 - \mu) - \tau$. As τ rises towards its upper bound $p - q(1 - \mu)$, the Pareto exponent becomes large and tends towards infinity. Consequently the Gini coefficient is reduced, and the wealth distribution becomes more equal. As the distribution becomes more highly peaked, the expression $a^* (1 - \mu) (1 - b) = ((1 - \mu) (1 - b))^P$,

representing the fraction of the q agents that inherit wealth above \underline{w} , declines. Consequently, the effect of estate taxes b decline as well: with small a^* the effect of b on $P = \frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau}$ becomes negligible. It follows that the higher is the value of τ , the more insignificant is the effect of the estate taxes b on the Pareto and Gini coefficients.³⁰ This can be seen from Figure 2 which plots the effect of b on P for various values of τ .

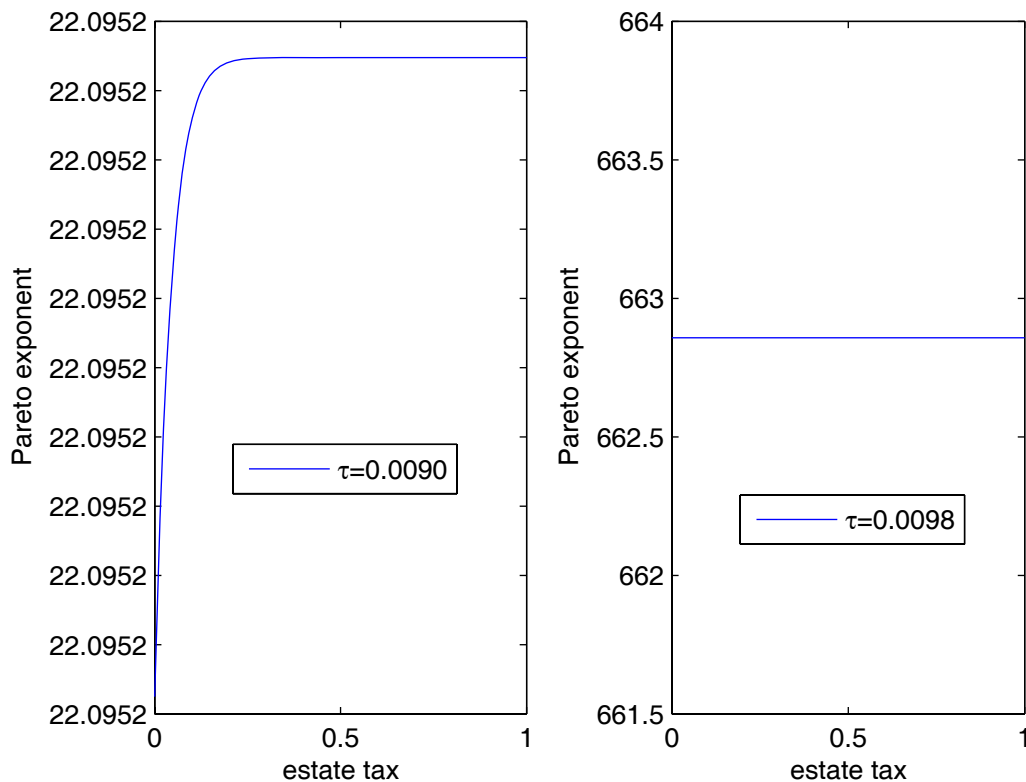


Figure 2:

It is also of interest to note the effect of bequests on the Pareto coefficient. An increase of the preference for bequest, χ , (or of the fraction q of agents with such preference) increases the fraction of wealth left as inheritance, $1 - \mu$. As a consequence, the aggregate growth rate of the economy increases without raising the growth rate of individual wealth, and the Pareto coefficient rises, decreasing wealth inequality.

³⁰Interestingly, Castaneda-Diaz Gimenez-Rios Rull (1993) also find small effects of estate taxes on the distribution of wealth in an equilibrium economy where the distribution of earnings are calibrated to match the wealth distribution in the US.

Fiscal policies (b, τ) do not only affect the Gini coefficient, but also the minimal wealth that can be supported by welfare, \underline{w} . Since tax collections finance subsidies so that the government budget remains balanced, discounted mean wealth, M , which we normalize to unity in our simulations, remains constant over time. At the stationary Pareto distribution, (26), we have

$$\underline{w} = \frac{P-1}{P}M \quad (31)$$

Thus as $P \rightarrow \infty$, $G \rightarrow 0$, perfect equality is reached where the minimum wealth is equal to mean wealth: $\underline{w} = M$.³¹

Normative effects of fiscal policies Instead of focusing on inequality, we may take social welfare to be the main target of fiscal policy. This of course requires the choice of a social welfare function.³² Chipman (1974), restricting his attention to Pareto distributions, showed that with additively separable social welfare functions, increasing the Pareto coefficient (and thus decreasing the Gini coefficient) does indeed increase social welfare if the mean (rather than the lower bound) of the distribution is kept constant. These results however are derived in a static context and cannot be applied directly to our model, as discussed below.

In the context of an additively separable (utilitarian) welfare criterion, we can inquire into the welfare properties of the stationary distribution of wealth $f(z)$.³³ This analysis naturally applies to both the case of "joy of giving" and to altruistic preferences for bequests. We can in fact express the social welfare of the agents alive at an arbitrary

³¹At the stationary distribution (26), the government budget constraint, under which tax collections exactly finance subsidies each period, can be written as (see the derivation in Appendix A):

$$\underline{w} = \frac{\tau + bq(1-\mu)M}{p - q(1-\mu)(1-b) \left(a^* + \frac{P}{P-1}(1-a^*) \right)} \quad (32)$$

where a^* solves (25). Of course, (31) and (32) are equivalent. This can be easily verified: substitute for M from (31) into (32), eliminate \underline{w} , solve for $\frac{P}{P-1}$, and verify that the solution is consistent with the definition of the Pareto exponent.

³²A large literature has explored the properties of social welfare functions, in particular those that are additively separable in individual utilities and that are increasing in the mean of the distribution of income and decreasing in a measure of its dispersion for all possible income or wealth distributions; see Samuelson (1965) for an early contribution to the subject. Atkinson (1970) and Newbery (1970) demonstrated that if individual utilities are strictly concave there exists no additively separable social welfare function that satisfies these properties. Later Sheshinski (1972) demonstrated that a Rawlsian welfare criterion would indeed satisfy them.

³³Our social welfare function weighs the well-being of future generations only through the preferences of those currently alive. An alternative approach, due to Caplin and Leahy(2004), is to give weight to future generations in addition to their implicit valuation through their current ancestors. Such a welfare function would put more weight on growth than a standard welfare function and moderate the capital income taxes that impede growth in our model.

time t as a function of the Pareto exponent P . Consider a representative agent who solves the maximization problem (1-2). Her optimal consumption-savings choice path is characterized in Section 2. Given an arbitrary discounted wealth z at time t , this time t discounted utility along the optimal path can be written as (see the derivation in Appendix A):

$$U(z) = \frac{1}{\theta + p} \left(\frac{g(1 + p\chi)}{\theta + p} + \ln \eta + p\chi \ln(\eta\chi)(1 - b) \right) + \frac{1 + p\chi}{\theta + p} \ln z \quad (33)$$

It is independent of t . Recall that a fraction $\frac{p-q}{p}$ of the agents have no preferences for bequests, that is, they have $\chi = 0$. For these agents, given an arbitrary discounted wealth z at time t , their time t discounted utility along the optimal path can be written as:

$$U_0(z) = \frac{1}{\theta + p} \left(\frac{g}{\theta + p} + \ln(p + \theta) \right) + \frac{1}{\theta + p} \ln z$$

The utilitarian social welfare of the agents alive at an arbitrary time, at the stationary wealth distribution $f(z)$ defined by (26), a Pareto distribution with mean M and exponent P , is:

$$\Omega(\underline{w}, P) = \frac{q}{p} \int_{\underline{w}}^{\infty} U(z)f(z)dz + \frac{p-q}{p} \int_{\underline{w}}^{\infty} U_0(z)f(z)dz$$

However, we set \underline{w} so that the government budget remains balanced. As discussed in footnote 3.1 above, the mean wealth M remains constant, and $\underline{w} = M \frac{P-1}{P}$. It is straightforward to show then that

$$\Omega(M, P) = \frac{1}{p + \theta} \left(\frac{g(1 + p\chi)}{p + \theta} + \ln \eta + p\chi \ln(\eta\chi)(1 - b) \right) + \frac{(1 + p\chi)}{p + \theta} \left(\ln \left(\frac{P-1}{P} M \right) + P^{-1} \right)$$

where $g = r - \theta - \tau$. Therefore,

$$\frac{\partial \Omega(M, P)}{\partial P} = \frac{(1 + p\chi)}{(p + \theta)^2} \frac{P^{-2}}{P - 1} > 0 \quad (34)$$

We can now consider the welfare effects of different fiscal policies, that is, of different combinations of estate taxes b and capital income taxes τ which satisfy government budget balance, (32). A policy (b, τ) affects on the Pareto exponent P of the stationary distribution $f(z)$ as P depends on τ and b . In a static framework without growth and without a bequest motive, the utilities of agents and the social welfare function does not directly depend on b or on τ except through the Pareto coefficient. Maximizing social welfare would then be equivalent to maximizing P , and given the egalitarian social welfare function, not surprisingly, it follows from (34) that social welfare would be maximized

under complete equality: $P = \infty$ and $G = 0$. However this is no longer the case in a dynamic context because both τ and b enter the social welfare function through g and through the bequest motive, in addition to entering through the Pareto coefficient³⁴. The derivatives of the social welfare function with respect to τ and b now become

$$\begin{aligned} \frac{\partial \Omega(M, b, \tau)}{\partial \tau} &= (p + \theta)^{-2} \left((1 + p\chi) \frac{P^{-2}}{P - 1} \frac{\partial P}{\partial \tau} - 1 \right) \\ &= (p + \theta)^{-2} \left(\frac{(P - 1)^{-1} (1 + p\chi)}{p - q \left\{ ((1 - \mu)(1 - b))^P (1 + P \ln((1 - \mu)(1 - b))) \right\}} - 1 \right) \end{aligned} \quad (35)$$

$$\begin{aligned} \frac{\partial \Omega(M, b, \tau)}{\partial b} &= (p + \theta)^{-1} \left(\frac{(1 + p\chi)}{p + \theta} \frac{P^{-2}}{P - 1} \frac{\partial P}{\partial b} - p\chi (1 - b)^{-1} \right) \\ &= (p + \theta)^{-1} \left[\frac{(1 + p\chi)}{(P - 1)(p + \theta)} \frac{\chi^{P-1} (p + \theta)^P (1 + p\chi)^{-1} (1 - b)^{P-1} q}{p - q \left\{ ((1 - \mu)(1 - b))^P (1 + P \ln((1 - \mu)(1 - b))) \right\}} - p(1 - b)^{-1} \right] \chi \end{aligned} \quad (36)$$

where $\Omega(M, b, \tau)$ is the social welfare function expressed explicitly as a function of the policy parameters b, τ ; also $\frac{\partial P}{\partial \tau}$ and $\frac{\partial P}{\partial b}$ are defined by (52) and (53) in the proof of Proposition 7 in Appendix A. From Proposition 7 we know that when the Pareto exponent is maximized at $\tau = p - q(1 - \mu)$, we have $\frac{\partial P}{\partial b} = 0$. Therefore if $\chi > 0$ for the subset q of agents, social welfare would decline in b due to the bequest motive, as is clear from (36). Consequently, the optimal b would be zero. If however τ has an interior solution so that $\frac{\partial P}{\partial b} > 0$, we cannot determine whether or not b will be interior. In fact it is clear from inspecting (35) that the value of τ that maximizes social welfare has to be less than $p - q(1 - \mu)$ because for $\tau \rightarrow p - q(1 - \mu)$ we have $(P - 1) \rightarrow \infty$, $((1 - \mu)(1 - b))^P P \rightarrow 0$ and $\frac{\partial \Omega(M, b, \tau)}{\partial \tau} < 0$.

Another interesting feature of social welfare function is that for small values of the bequest parameter χ we have $\frac{\partial \Omega(M, b, \tau)}{\partial b} < 0$, so that the maximizing social welfare requires setting $b = 0$. The reason is that for small values of χ , the agent sets a high μ and therefore leaves a small bequest. The negative effect of b on social welfare through its reduction of bequests, given by $-p\chi(1 - b)^{-1}$, dominates the positive effect of b on social welfare through the Pareto exponent. This is because as $\chi \rightarrow 0$, $(1 - \mu)^P \rightarrow 0$ as χ^P with $P > 1$, so that for small χ the expression in square brackets in the last two lines of (36)

³⁴Unequal wealth distributions can be constrained optimal in economies in which hidden effort or unobservable skills and endogenous labor supply affect individual earnings, as in Atkeson-Lucas (1995), Phelan (1998), or Kocherlakota (2005).

is negative.³⁵

For the parameters given by (30), Figure 3 shows the plot of the social welfare function. Welfare is maximized at $(b, \tau) = (0, 0.0095)$ where the maximum value of τ is

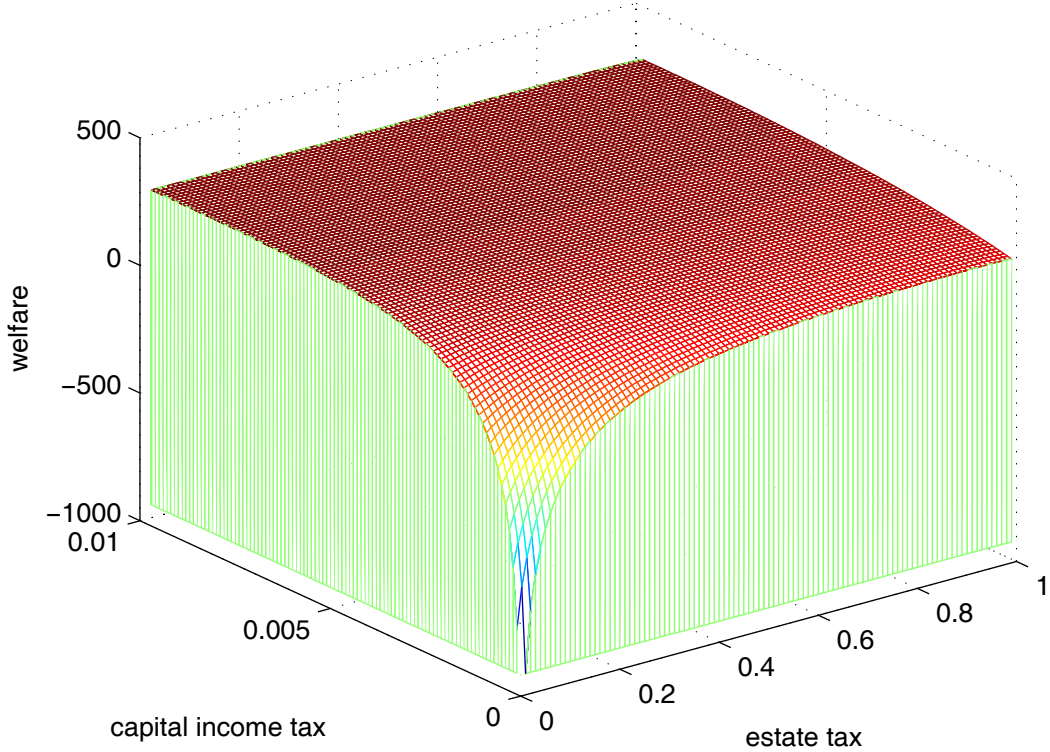


Figure 3:

³⁵Note that, as noted in footnote 20, for technical reasons we do not allow our agents to anticipate welfare subsidies to their children when optimally choosing bequests. For both the "joy of giving" and the altruistic specification of preferences for bequest this would tend to reduce redistributive taxes at an optimum, as welfare subsidies would induce agents to reduce the investment in assets in the early wealth accumulation stages.

Note also that our normative fiscal policy analysis changes if we restrict to a formulation of "joy of giving" bequests which depends on gross rather than net bequests. The utility of bequests in this formulation would simply be $\chi \ln(\omega)$, without the term $(1 - b)$. Under logarithmic utility the share of consumption η and the portfolio allocation determined by μ are independent of b , and only the social welfare function is affected. Now however the welfare maximizing $b = 0.990$, still less than the maximum of 1 but much higher than zero. When agents derive utility from gross bequests, it becomes optimal, given the egalitarian social welfare function, to redistribute wealth with both high capital and high estate taxes.

$p - q(1 - \mu) = 0.0097$, so τ is indeed interior. Figure 4a below shows that social welfare does decline with b for $\tau = 0.0095$ for $\chi = 10$. The Pareto exponent is $P = 71.3846$, the lower bound on wealth is $\underline{w} = 0.986$, the fraction of the q agents who inherit more than \underline{w} is $(1 - \mu)(1 - b)a^* = (1 - \mu)^{71.3846} = (2.6585)(10)^{-23}$ and the fraction of wealth that the q agents hold in non-inheritable annuitized form is $\mu = 0.5172$. Figure 4b shows the same, but for a much smaller bequest parameter, $\chi = 0.01$. Despite the small χ , welfare still declines with b for the reasons discussed above, and it is maximized at $(b, \tau) = (0, 0.0158)$ where the maximum allowed value of τ is $p - q(1 - \mu) = 0.0159987$. Now however the welfare maximizing capital tax is higher³⁶ at $\tau = 0.0157$, the Pareto exponent is lower at $P = 53.4631$, the lower bound on wealth is $\underline{w} = 0.9813$, the fraction of the q agents who inherit more than \underline{w} is $(1 - \mu)(1 - b)a^* = (1 - \mu)^{53.4631} = 4.8385(10)^{-228}$ and the fraction of wealth that the q agents hold in non-inheritable annuitized form is $\mu = 0.9999$.

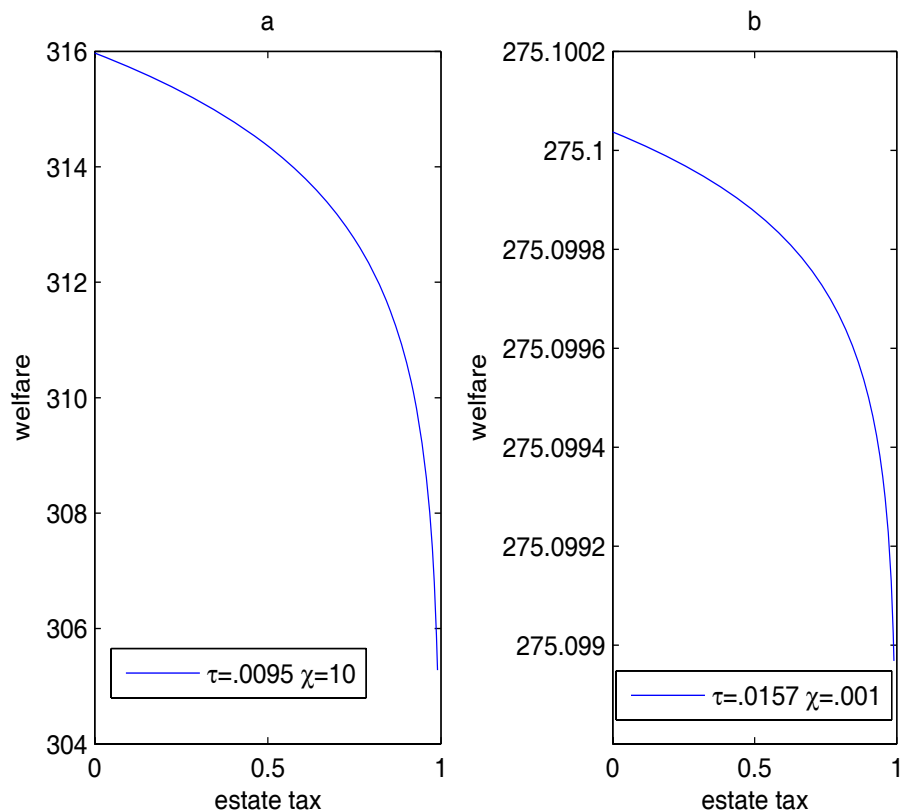


Figure 4:

³⁶The capital taxes are higher despite the direct effect of a lower bequest motive χ because a low χ implies a higher μ and a lower Pareto exponent, which tends to make wealth distribution more unequal.

Thus for both $\chi = 10$ and $\chi = 0.001$, at the social welfare optimum of for the stationary distribution $f(z)$ estate taxes $b = 0$, capital taxes are interior but close to their maximum allowed value of $p - q(1 - \mu)$, and in both cases almost all the population is concentrated just below the mean wealth of 1. However, the egalitarianism implicit in the social welfare function is implemented through capital rather than through estate taxes. Depending on the bequest motive χ , this comes at the expense of growth of almost 1% to 1.5%.

4 Discussion and Conclusions

The distribution of wealth is Pareto in our economy due to the interaction of economic and demographic mechanisms with the following basic properties: *i*) individual wealth grows exponentially (at rate g) in wealth, *ii*) a fraction of the newborn agents, at any time, are born at the lower boundary of the wealth distribution, which also grows exponentially (at rate g'), but slower than individual wealth. We have obtained these properties endogenously from the postulated optimal consumption-saving problem of individual agents in an overlapping generation economy with constant probability of death and the redistributive fiscal policy of a government which balances the budget.

In fact this mechanism operates more generally to generate Pareto distributions of wealth. First of all, notice that the analysis of the distribution of wealth in our economy is equivalent to the analysis of the distribution of *per-capita* wealth in an economy in which all agents have preferences for bequests, and hence all agents in the economy inherit, but at any time t there is an inflow of $p - q$ agents from outside, e.g., due to immigration, at the lower bound of wealth. Notably, in this case the population of the economy is not constant but rather grows at a constant rate, and per-capita wealth has a Pareto distribution. The Pareto exponent can be solved for just as in Propositions 3-6, once the parameters (including the death rate and the individual and aggregate growth rates) have been normalized for population growth.

Another economy for which our analysis readily extends is the following. Consider a dynastic infinite horizon economy in which all agents face a Poisson probability p that their wealth is wiped out unless invested in a protected insurance account. Let $\omega(s, t)$ denote the amount of wealth deposited at time t by an agent born at time s in the protected insurance account. Let r denote the interest rate on wealth at time t (no annuity component). Assume that the insurance account pays a return $r - \delta$, where $\delta - p \geq 0$ is a measure of market imperfection.

The maximization problem of an agent born at time s , in recursive form, is:

$$V(w(s, t)) = \max_{c, \omega} \int_t^{\infty} e^{(\theta+p)(t-v)} (\ln c(s, v) + pV(\omega(s, v))) dv$$

subject to

$$\frac{dw(s,t)}{dt} = rw(s,t) - \delta\omega - c(s,t)$$

and the Transversality condition. Proceeding as in the Overlapping Generations economy with altruistic agents (see Appendix A), we can show that

$$c = \theta w, \quad \omega = \frac{p}{\delta} w$$

When $p = \delta$ and insurance is without friction, then all of the wealth is deposited in the insurance account.

It follows immediately that our whole analysis of the dynamics of the distribution of wealth can be extended to this dynastic economy, once the parameter χ is taken to be endogenous and $1 - \mu$ is appropriately redefined.

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4.1.1 Appendix A: Proofs - for completeness

Proof of Prop. 1. The dynamic equation for wealth accumulation is

$$\frac{dw(s, t)}{dt} = (r + p - \tau) w(s, v) - p\omega(s, v) - c(s, v)$$

First order conditions include

$$\omega(s, t) = \chi c(s, t) \tag{37}$$

$$\dot{c}(s, t) = (r - \tau - \theta) c(s, t) \tag{38}$$

The aggregate dynamics for the agent can then be written as:

$$\dot{w}(t, s) = (r + p - \tau) w(t, s) - (p\chi + 1) c(s, v)$$

Postulating $c = \eta w$, after some algebra,

$$\frac{dw(s, t)}{dt} = ((r + p - \tau) - \eta(p\chi + 1)) w(s, v) \tag{39}$$

So that, equating 38 and 39 we verify that in fact

$$c = \eta w, \quad \text{with } \eta = \frac{(p + \theta)}{p\chi + 1} \tag{40}$$

Furthermore, by (37),

$$\omega = \chi\eta w, \quad \text{with } \eta = \frac{(p + \theta)}{p(1 - b)^{-1}\chi + 1}$$

Finally, using

$$\dot{w}(t, s) = (r + p - \tau) w(t, s) - (p\chi + 1)\eta w(t, s)$$

and

$$\eta = \frac{(p + \theta)}{p\chi + 1}$$

we can solve for the growth of the agent's wealth, which we denote g :

$$g = r - \tau - \theta \tag{41}$$

Derivation of the PDE, equation (11). Consider the Chapman-Kolmogorov equation which governs the dynamics of $f(w, t)$. Let $w_1 > w_l(t)$. The mass of wealth in the interval (w_1, w) at time $t + \Delta$ is $\int_{w_1}^w f(w, t + \Delta) dw$. At a first order approximation

this mass has two components. First, since individual wealth grows at rate g , it contains the mass of agents who have wealth in the interval $((1 - g\Delta)w_1, (1 - g\Delta)w)$ at time t and are alive at $t + \Delta$. Secondly, through the boundary condition it contains the contribution of those newborns who inherit a fraction of their parents' wealth: the newborns at time t who do not inherit from their parents, or whose inheritance fall below $w_l(t)$ add to the density at $w_l(t)$.

Summarizing, the Chapman-Kolmogorov equation can then formally be written as:

$$\int_{w_1}^w f(s, t + \Delta) dw = (1 - p\Delta) \int_{(1-g\Delta)w_1}^{(1-g\Delta)w} f(s, t) dw + q\Delta \int_{\sigma(w_1)}^{\sigma(w)} f(s, t) ds + o(\Delta)$$

Differentiating with respect to w and ignoring second-order terms (terms in Δ^2),

$$f(w, t + \Delta) = (1 - p\Delta)(1 - g\Delta)f((1 - g\Delta)w, t) + q\Delta \frac{\partial \sigma(w)}{\partial w} f(\sigma(w), t)$$

Rearranging,

$$\begin{aligned} & \frac{f(w, t + \Delta) - f(w, t)}{\Delta} = \\ = & \frac{f(((1 - g\Delta)w, t) - f(w, t) - (\Delta p + \Delta g)f(((1 - g\Delta)w, t) + q\Delta \frac{\partial \sigma(w)}{\partial w} f(\sigma(w), t))}{\Delta} \end{aligned}$$

and, letting $\Delta \rightarrow 0$,

$$\frac{\partial f(w, t)}{\partial t} = -(p + g)f(w, t) + q \frac{\partial \sigma(w)}{\partial w} f(\sigma(w), t) - g \frac{\partial f(w, t)}{\partial w}$$

Derivation of the boundary condition, (13). The two terms of (13) are, respectively, the density of the newborns with no inheritance and the density of the newborn with inheritance lower than \underline{w} .

The first term of (13) can be derived from the age distribution. In particular the density of newborn agents (agents of age $a = 0$) with no inheritance is $p - q$. The wealth $w(a)$ of an agent of age a born with wealth \underline{w} is $w(a) = \underline{w}e^{ga}$. Operating the appropriate change of variable to obtain the distribution of wealth from the distribution of age, and evaluating at $w = \underline{w}$, we obtain $\frac{p-q}{g} \frac{1}{\underline{w}}$. The second term is straightforwardly derived.

Proof of Lemma 1 To solve (11) under (16) and (15) we apply the "method of characteristics" as detailed in Appendix C. Let the characteristic space (τ, t) be defined by

$$\frac{dz}{d\tau} = (g - g')z, \quad \frac{dt}{d\tau} = 1.$$

Let $z(0) = m$ and $t(0) = 0$. In the characteristic space the PDE (11) is then reduced to the following differential equation:

$$\frac{d(f(z(\tau), \tau))}{d\tau} = -(p + g - g') f(z(\tau), \tau) + q \frac{\partial \sigma(z)}{\partial z} f(\sigma(z(\tau)), \tau) \quad (42)$$

It can be verified that (42) has solution:

$$f(z(\tau), \tau) = e^{-(p+g-g')\tau} f(m, 0) + \int_0^\tau q \frac{\partial \sigma(z)}{\partial z} f(\sigma(z(\eta)), \eta) e^{(p+g-g')(\eta-\tau)} d\eta \quad (43)$$

The characteristic space is split along the characteristic $z = \underline{w}e^{(g-g')\tau}$. In particular, for $z \geq \underline{w}e^{(g-g')\tau}$ the solution to the PDE is determined by the initial condition, while for $z < \underline{w}e^{(g-g')\tau}$ the solution is instead determined by the boundary condition through the inverse transformation $\tau(z, y) = \ln \frac{z}{y} \frac{1}{(g-g')}$. Then, substituting back into the original space (z, t) , we obtain

$$f(z, t) = \begin{cases} \left(\frac{z}{\underline{w}} \right)^{-\frac{p}{g-g'}-1} f(\underline{w}, t - \tau(z, \underline{w})) + \\ \quad + q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y), t - \tau(z, y)) (y)^{\left(\frac{p}{g-g'}\right)} (g - g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy & \text{for } z \in (\underline{w}, \underline{w}e^{(g-g')t}) \\ e^{-(p+g-g')t} h(z e^{(g-g')t}) \\ \quad + q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y), t - \tau(z, y)) (y)^{\left(\frac{p}{g-g'}\right)} (g - g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy & \text{for } z \geq \underline{w}e^{(g-g')t} \end{cases}$$

Proof of Prop. 2. Consider the dynamics of $f(z, t)$ as characterized by (17) in Lemma 1. Consider discounted wealth levels $z \geq \underline{w}e^{(g-g')t}$. In this region, the density an any time t is

$$e^{-(p+g-g')t} h\left(z e^{(g-g')t}\right) + q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y), t - \tau(z, y)) (y)^{\left(\frac{p}{g-g'}\right)} (g - g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy$$

Notice that, if $\sigma(y) = y$, the density in the region $z \geq \underline{w}e^{(g-g')t}$ at time t is larger than in the case $\sigma(y) > y$. But, when $\sigma(y) = y$ (17) can be easily solved to obtain that

$$f(z, t) = e^{-(p-q+g-g')t} h\left(z e^{-(g-g')t}\right), \quad \text{for } z \geq \underline{w}e^{(g-g')t}.$$

It is now straightforward to notice that $e^{-(p-q+g-g')t} h\left(z e^{-(g-g')t}\right)$ vanishes for $t \rightarrow \infty$.

We conclude that at the stationary distribution the whole mass is in the region $z \in (\underline{w}, \underline{w}e^{(g-g')t})$. As a consequence, then, from (17),

$$f(z) = \left(\frac{z}{\underline{w}} \right)^{-\frac{p}{g-g'}-1} f(\underline{w}) + q \int_{\underline{w}}^z \frac{\partial \sigma(y)}{\partial y} f(\sigma(y)) (y)^{\left(\frac{p}{g-g'}\right)} (g - g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} dy$$

The subsequent Propositions 3, 4 and 5 give the analytic solutions of the stationary distributions.

Proof of Prop. 3. Substituting (20), (8), and $\mu = 1$, $q = 0$ into (17) reduces it to

$$f(z, t) \begin{cases} \frac{p}{p-\tau} \frac{1}{\underline{w}} \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{p-\tau}+1\right)} & \text{for } z \in (\underline{w}, \underline{w}e^{(p-\tau)t}) \\ e^{-(p+p-\tau)t} h(z) & \text{for } z \geq \underline{w}e^{(g-g')t} \end{cases} \quad (44)$$

for which the boundary condition holds.

Proof of Prop. 4 Consider $z \in (\underline{w}, \underline{w}e^{(g-g')t})$. In this range, substituting (20), and $b = 0$, in (17), it follows that $f(z, t)$ is stationary (independent of t), and hence it satisfies the integral equation (18), which in this case takes the form:

$$f(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) + q \int_{\underline{w}}^z (y)^{\left(\frac{p}{g-g'}\right)} (g-g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} f(y) dy \quad (45)$$

This is a Volterra integral equation of the second type, with separable kernel, for which a closed form solution exists and is discussed in Appendix D. Applying this solution, we obtain,

$$f(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) + q (g-g')^{-1} \int_{\underline{w}}^z z^{-\left(\frac{p}{g-g'}+1-q(g-g')^{-1}\right)} j^{\left(\frac{p}{g-g'}-q(g-g')^{-1}\right)} \left(\frac{j}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) dj \quad (46)$$

Straightforward algebraic manipulations, together (20), are now enough to produce the result.

Proof of Prop. 5 The integral equation in this case, after the transformation $j = \sigma(y) = \frac{y}{(1-\mu)(1-b)}$ is reduced to:

$$f(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) + q (g-g')^{-1} \cdot \int_{\frac{\underline{w}}{(1-\mu)(1-b)}}^{\frac{z}{(1-\mu)(1-b)}} f(j) \left[((1-\mu)(1-b)j)^{\left(\frac{p}{g-g'}\right)} z^{-\left(\frac{p}{g-g'}+1\right)} \right] dj \quad (47)$$

where $g-g' = p-q(1-\mu)-\tau$. We guess:

$$f(z) = \frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu)-\tau} \underline{w}^{\frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu)-\tau}} z^{-\left(\frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu)-\tau}+1\right)} \quad (48)$$

and substitute into the integral equation. Let $f(\underline{w}) = \frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu)-\tau} \frac{1}{\underline{w}}$. We obtain

$$\begin{aligned}
f(z) &= \frac{z^{-\left(\frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu)-\tau}+1\right)}}{\underline{w}} f(\underline{w}) = \\
& \frac{z^{-\left(\frac{p}{g-g'}+1\right)}}{\underline{w}} f(\underline{w}) + q(g-g')^{-1} (z)^{-\left(\frac{p}{g-g'}+1\right)} \cdot \\
& \cdot \int_{((1-\mu)(1-b))^{-1}\underline{w}}^{((1-\mu)(1-b))^{-1}z} \left(\frac{j}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1-aq(g-g')^{-1}(1-\mu)(1-b)\right)} f(\underline{w}) ((1-\mu)(1-b)j)^{\frac{p}{g-g'}} dj
\end{aligned}$$

and, after some algebraic manipulations,

$$\begin{aligned}
\frac{z^{-\left(\frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu)-\tau}+1\right)}}{\underline{w}} f(\underline{w}) &= \frac{z^{-\left(\frac{p}{g-g'}+1\right)}}{\underline{w}} f(\underline{w}) + \\
+ q(g-g')^{-1} ((1-\mu)(1-b))^{\frac{p}{g-g'}} \frac{z^{-\left(\frac{p}{g-g'}+1\right)}}{\underline{w}} \underline{w}^{-aq(g-g')^{-1}((1-\mu)(1-b))} f(\underline{w}) \\
\cdot \int_{((1-\mu)(1-b))^{-1}\underline{w}}^{((1-\mu)(1-b))^{-1}z} j^{-1+aq(g-g')^{-1}(1-\mu)(1-b)} dj
\end{aligned}$$

and hence

$$\begin{aligned}
& \frac{z^{-\left(\frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu)-\tau}+1\right)}}{\underline{w}} f(\underline{w}) = \\
& = \frac{z^{-\left(\frac{p}{g-g'}+1\right)}}{\underline{w}} f(\underline{w}) \left(1 + a^{-1} \underline{w}^{-aq(g-g')^{-1}(1-\mu)(1-b)} \left((1-\mu)(1-b) \right)^{\frac{p-aq(1-\mu)(1-b)}{g-g'}-1} \right. \\
& \quad \left. \cdot \left(z^{aq(g-g')^{-1}(1-\mu)(1-b)} - \underline{w}^{aq(g-g')^{-1}(1-\mu)(1-b)} \right) \right) \\
& = \frac{z^{-\left(\frac{p}{g-g'}+1\right)}}{\underline{w}} f(\underline{w}) \left(1 + a^{-1} \left((1-\mu)(1-b) \right)^{\frac{p-aq((1-\mu)(1-b))}{g-g'}-1} \right. \\
& \quad \left. \left(\frac{z^{aq(g-g')^{-1}(1-\mu)(1-b)}}{\underline{w}} - 1 \right) \right)
\end{aligned}$$

$$\text{Let } a^{-1} \left((1-\mu)(1-b) \right)^{\frac{p-aq(1-\mu)(1-b)}{g-g'}-1} = 1, \text{ or}$$

$$a = \left((1-\mu)(1-b) \right)^{\frac{p-aq(1-\mu)(1-b)}{g-g'}-1}$$

This is fixed point equation which has a unique solution, $a^* < 1$. In fact, it is easily checked that $\left((1-\mu)(1-b) \right)^{\frac{p-aq((1-\mu)(1-b))}{g-g'}-1} = \left((1-\mu)(1-b) \right)^{\frac{p-aq(1-\mu)(1-b)}{p-q((1-\mu))- \tau}-1}$ is strictly positive for $a = 0$, it has a negative derivative with respect to a , and it is less than 1 for

$a = 1$. Consequently,

$$\begin{aligned}
& \frac{z}{\underline{w}} - \left(\frac{p-a^*q((1-\mu)(1-b))}{g-g'} + 1 \right) f(\underline{w}) = \\
& \frac{z}{\underline{w}} - \left(\frac{p}{g-g'} + 1 \right) f(\underline{w}) \left(1 + \left(\frac{z}{\underline{w}} - 1 \right) \right) \\
& = \frac{z}{\underline{w}} - \left(\frac{p-a^*q((1-\mu)(1-b))}{g-g'} + 1 \right) f(\underline{w})
\end{aligned}$$

and the guess is verified.

It remains to show that the boundary condition holds for the stationary distribution. As shown in the section "Derivation of the government budget constraint" below,

$$\begin{aligned}
q \int_{\underline{w}}^{\sigma(\underline{w})} f(z) dz &= q \left(1 - ((1-\mu)(1-b))^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))^{-\tau}}} \right) \\
&= q(1 - (1-\mu)(1-b)a)
\end{aligned}$$

so that the boundary condition (19) can be written as

$$f(\underline{w}) = \frac{p-q}{(g-g')\underline{w}} + \frac{q(1 - (1-\mu)(1-b)a)}{(g-g')\underline{w}} \quad (49)$$

Evaluating the stationary distribution at \underline{w}

$$\begin{aligned}
f(\underline{w}) &= \frac{p-aq(1-\mu)(1-b)}{g-g'} \underline{w}^{-1} \\
f(\underline{w}) &= \frac{p-q}{g-g'} \underline{w}^{-1} + \frac{q(1-a(1-\mu)(1-b))}{g-g'} \underline{w}^{-1} = \Psi
\end{aligned} \quad (50)$$

which is identical to (49).

Proof of Prop. 6 The integral equation in this case, after the transformation $j = \sigma(y) = \frac{y-x}{(1-\mu)(1-b)}$ is reduced to:

$$\begin{aligned}
f(z) &= \left(\frac{z}{\underline{w}} \right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) \\
&+ q(g-g')^{-1} \int_{\underline{w}}^{\frac{z-x}{(1-\mu)(1-b)}} f(j) \left[((1-\mu)(1-b)j+x)^{\left(\frac{p}{g-g'}\right)} (z)^{-\left(\frac{p}{g-g'}+1\right)} \right] dj
\end{aligned}$$

A lower bound on $f(z)$, $l(z)$ is obtained by the solution to

$$\begin{aligned}
l(z) &= \left(\frac{z}{\underline{w}} \right)^{-\left(\frac{p}{g-g'}+1\right)} l(\underline{w}) \\
&+ q(g-g')^{-1} \int_{\underline{w}}^{\frac{z-x}{(1-\mu)(1-b)}} f(j) \left[((1-\mu)(1-b)j+x)^{\left(\frac{p}{g-g'}\right)} (z)^{-\left(\frac{p}{g-g'}+1\right)} \right] dj = \\
&= \left(\frac{z}{\underline{w}} \right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w})
\end{aligned}$$

$l(z)$ is a power function with exponent $\frac{p}{p-q(1-\mu)-\tau}$, which is a Pareto distribution integrating to unity if defined over $w \geq f(\underline{w}) \left(\frac{p}{p-q(1-\mu)-\tau}\right)^{-1}$.

An upper bound on $f(z)$, $u(z)$ is obtained by the solution to

$$u(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} u(\underline{w}) + q(g-g')^{-1} \int_{\underline{w}}^{\frac{z}{(1-\mu)(1-b)}} u(j) j^{\frac{p}{g-g'}} z^{-\left(\frac{p}{g-g'}+1\right)} dj$$

since $1-\mu)(1-b)j+x \leq j$ by construction. Adapting the proof of Prop. 5, we can show that $u(z)$ is a power function with exponent

$$\frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau} > 1, \quad \text{for } 0 < a^* < 1 \text{ satisfying (25)}$$

which is a Pareto distribution integrating to one if defined for $w \geq f(\underline{w}) \left(\frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau}\right)^{-1}$. The distribution $f(z)$ for $z \geq f(\underline{w}) \left(\frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau}\right)^{-1}$ lies in between $u(z)$ and $l(z)$ ³⁷, both of which converge to zero for large z and therefore it is approximated by

$$f(z) = \left(\frac{z}{\underline{w}}\right)^{-\left(\frac{p}{g-g'}+1\right)} f(\underline{w}) + q(g-g')^{-1} \int_{\underline{w}}^{\frac{z}{(1-\mu)(1-b)}} f(j) \left[((1-\mu)(1-b)j)^{\left(\frac{p}{g-g'}\right)} (z)^{-\left(\frac{p}{g-g'}+1\right)} \right] dj$$

which has the solution derived in the proof of Prop. 5: a Pareto distribution with exponent

$$\frac{p-a^*q(1-\mu)(1-b)}{p-q(1-\mu)-\tau} > 1, \quad \text{for } 0 < a^* < 1 \text{ satisfying (25)}$$

Proof of Proposition 7: Since

$$P = \frac{p - ((1-\mu)(1-b))^P q}{p - q((1-\mu)) - \tau} \tag{51}$$

The right side 51 is increasing in P , for $P = 1$ it is larger than 1, and for $P \rightarrow \infty$ it is finite. Therefore we focus on the unique solution of $P \geq 1$. Since $p - q((1-\mu)) - \tau \geq 0$, and $0 \leq ((1-\mu)(1-b))^P \leq 1$ it follows that $\lim_{\tau \rightarrow (p-q((1-\mu)))} P = \infty$. Computing the derivatives of P , and substituting for $p - q((1-\mu))$ from 51 we get

$$\frac{dP}{d\tau} = \frac{P^2}{p - q \left\{ ((1-\mu)(1-b))^P (1 + P \ln((1-\mu)(1-b))) \right\}} > 0 \tag{52}$$

³⁷Alternatively the solution of $f(z)$ may be explicitly written as the limiting solution obtained by the successive approximation method (see Polyanin and Manzhairov, section 9.9). The it is possible to show that the iterated kernels of $f(z)$ lie below the iterated kernels of $u(z)$.

$$\frac{dP}{db} = \frac{P^2 ((1-\mu)(1-b))^{P-1} q(1-\mu)}{p-q \left\{ ((1-\mu)(1-b))^P (1+P \ln((1-\mu)(1-b))) \right\}} \geq 0 \quad (53)$$

Note that $\frac{dP}{db} = 0$ would obtain only if $P \rightarrow \infty$ and $(1-\mu)(1-b) < 1$. As shown, this is indeed the case only if $\tau \rightarrow (p-q((1-\mu)))$ and may also be ascertained directly by applying L'Hopital's rule to 53. To do this first apply L'Hopital's rule twice to $\frac{P^2}{((1-\mu)(1-b))^{-P+1}}$ and once to $\frac{P}{((1-\mu)(1-b))^P}$ by differentiating with respect to τ , and show that both expressions converge to zero as $\tau \rightarrow (p-q((1-\mu)))$ because $\lim_{\tau \rightarrow (p-q((1-\mu)))} P = \infty$. Then substitute into the expression $\frac{dP}{db}$ to see that $\lim_{\tau \rightarrow p-q((1-\mu))} \frac{dP}{db} = \frac{0}{p}$.

Derivation of the government budget constraint, (32). Consider the government expenditures (10), written in terms of discounted wealth and evaluated at the stationary distribution $f(z)$:

$$(p-q)\underline{w} + q \int_{\underline{w}}^{((1-b)(1-\mu))^{-1}\underline{w}} (\underline{w} - (1-b)(1-\mu)z) f(z) dz \quad (54)$$

Furthermore, the stationary distribution is

$$\begin{aligned} f(z) &= f(\underline{w}) \frac{z^{-\left(\frac{p-a^*q((1-\mu)(1-b))}{(p-q((1-\mu))-\tau)}+1\right)}}{\underline{w}} = \\ &= \frac{p-aq((1-\mu)(1-b))}{(p-q((1-\mu))-\tau)} \frac{\underline{w}^{\frac{p-a^*q((1-\mu)(1-b))}{p-q((1-\mu))-\tau}}}{z^{-\left(\frac{p-a^*q((1-\mu)(1-b))}{p-q((1-\mu))-\tau}+1\right)}} \end{aligned}$$

We proceed first by computing $\int_{\underline{w}}^{((1-b)(1-\mu))^{-1}\underline{w}} (1-b)(1-\mu)zf(z)dw$:

$$\begin{aligned}
& \frac{p-aq((1-\mu)(1-b))}{(p-q((1-\mu))-\tau)} \underline{w}^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}} \cdot \\
& \cdot \int_{\underline{w}}^{((1-\mu)(1-b))^{-1}\underline{w}} z^{-\left(\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}+1\right)} (1-\mu)(1-b)zdz \\
= & \frac{p-aq((1-\mu)(1-b))}{(p-q((1-\mu))-\tau)} \underline{w}^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}} \cdot \\
& \cdot \left(-\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau} + 1 \right)^{-1} (1-\mu)(1-b) \\
& \cdot \left(((1-\mu)(1-b))^{\left(\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}-1\right)} - 1 \right) \underline{w}^{-\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}+1} \\
= & \left(\frac{p-aq((1-\mu)(1-b))}{-p+aq((1-\mu)(1-b))+p-q((1-\mu))-\tau} \right) \underline{w} \\
& \left(((1-\mu)(1-b))^{\left(\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}\right)} - 1 \right) (1-\mu)(1-b) \\
= & (1-\mu)(1-b) \frac{p-aq((1-\mu)(1-b))}{q(1-\mu)(1-a(1-b))+\tau} \\
& \left(1 - ((1-\mu)(1-b))^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}-1} \right) \underline{w}
\end{aligned}$$

Furthermore we compute $\int_{\underline{w}}^{((1-b)(1-\mu))^{-1}\underline{w}} f(z)dw$:

$$\begin{aligned}
& \frac{p-aq((1-\mu)(1-b))}{(p-q((1-\mu))-\tau)} \underline{w}^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}} \int_{\underline{w}}^{((1-\mu)(1-b))^{-1}\underline{w}} \left(z^{-\left(\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}+1\right)} \right) dz \\
= & \left\{ \left(\frac{p-aq((1-\mu)(1-b))}{(p-q((1-\mu))-\tau)} \right) \underline{w}^{\left(\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}\right)} \left(-\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau} \right)^{-1} \right\} \\
& \cdot \left(((1-\mu)(1-b))^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}} - 1 \right) \underline{w}^{-\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}} \\
= & \left(1 - ((1-\mu)(1-b))^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}} \right)
\end{aligned}$$

Substituting the computations in (54), we conclude that government expenditures are:

$$(p-q)\underline{w} + q\underline{w} \left(\begin{array}{c} \left(1 - ((1-\mu)(1-b))^{\frac{p-aq((1-\mu)(1-b))}{p-q((1-\mu))-\tau}-1} \right) \\ - (1-\mu)(1-b) \frac{p-aq(1-\mu)(1-b)}{q(1-\mu)(1-a(1-b))+\tau} \\ \left(1 - ((1-\mu)(1-b))^{\frac{p-aq(1-\mu)(1-b)}{p-q(1-\mu))-\tau}-1 \right) \end{array} \right)$$

and therefore that the government budget constraint can be written as:

$$\begin{aligned} & \frac{w}{(\tau + bq(1 - \mu))W(0)} \begin{pmatrix} (p - q) + q \left(1 - ((1 - \mu)(1 - b))^{\frac{p - aq(1 - \mu)(1 - b)}{p - q((1 - \mu)) - \tau} - 1} \right) \\ \left(1 - (1 - \mu)(1 - b)^{\frac{p - aq(1 - \mu)(1 - b)}{q(1 - \mu)(1 - a(1 - b)) + \tau}} \right) \end{pmatrix} \\ & = (\tau + bq(1 - \mu))W(0) \end{aligned}$$

where without loss of generality we set $M = W(0) = 1$.

Derivation of the discounted utility along the optimal path, (33). In our economy, the optimal consumption-savings path of an arbitrary agent is characterized by (3). Along this path, it is straightforward to compute

$$U(z) = \int_t^\infty e^{(\theta+p)(t-\nu)} (\ln \eta w(t, \nu) + p\chi \ln(1 - b)\chi \eta w(t, \nu)) d\nu$$

where $w(t, \nu) = ze^{g(\nu-t)}$; or,

$$U(z) = \int_t^\infty e^{(\theta+p)(t-\nu)} (\ln \eta + \ln z + g(\nu - t) + p\chi \ln(1 - b)\chi \eta + p\chi \ln z + p\chi g(\nu - t)) d\nu$$

We proceed to analyze separately three components of $U(z)$:

- i) $\int_t^\infty e^{(\theta+p)(t-\nu)} (\ln \eta + p\chi \ln(1 - b)\chi \eta) d\nu$;
- ii) $\int_t^\infty e^{(\theta+p)(t-\nu)} (1 + p\chi) g(\nu - t) d\nu$; and finally,
- iii) $\int_t^\infty e^{(\theta+p)(t-\nu)} (1 + p\chi) \ln z d\nu$.

i) Integrating,

$$\int_t^\infty e^{(\theta+p)(t-\nu)} (\ln \eta + p\chi \ln(1 - b)\chi \eta) d\nu = \frac{1}{\theta + p} (\ln \eta + p\chi \ln(1 - b)\chi \eta)$$

ii) Integrating by parts,

$$\begin{aligned} & \int_t^\infty e^{(\theta+p)(t-\nu)} (1 + p\chi) g(\nu - t) d\nu = \\ & = g(1 + p\chi) \left(-\frac{1}{\theta + p} [e^{(\theta+p)(t-\nu)}(\nu - t)]_t^\infty + \frac{1}{\theta + p} \int_t^\infty e^{(\theta+p)(t-\nu)} d\nu \right) = \\ & = g(1 + p\chi) \left(-\frac{1}{\theta + p} [e^{(\theta+p)(t-\nu)(\nu-t)}]_t^\infty - \frac{1}{(\theta + p)^2} [e^{(\theta+p)(t-\nu)}]_t^\infty \right) = \\ & = \frac{g(1 + p\chi)}{(\theta + p)^2} \end{aligned}$$

iii) Integrating,

$$\int_t^\infty e^{(\theta+p)(t-\nu)} (1+p\chi) \ln z d\nu = \frac{1+p\chi}{\theta+p} \ln z$$

Adding up,

$$U(z) = \frac{1}{\theta+p} \left(\frac{g(1+p\chi)}{\theta+p} + \ln \eta + p\chi \ln (1-b)\chi\eta \right) + \frac{1+p\chi}{\theta+p} \ln z$$

Optimal Consumption-Savings for Altruistic Agents. The maximization problem of an agent born at time s , in recursive form, is:

$$V(w(s, t)) = \max_{c, \omega} \int_t^\infty e^{(\theta+p)(t-v)} (\ln c(s, v) + p\alpha V(\omega(s, v))) dv$$

subject to

$$\frac{dw(s, t)}{dt} = (r+p)w(s, t) - p\omega - c(s, t)$$

and the Transversality condition

We guess

$$V(\omega) = A + B \ln \omega$$

Under the guess the Hamiltonian is

$$H = \ln c + pA\alpha + pB\alpha \ln \omega + \lambda((r+p)w - p\omega - c)$$

and the associated First Order Conditions are

$$\begin{aligned} c^{-1} &= \lambda; & \frac{\dot{c}}{c} &= -\frac{\dot{\lambda}}{\lambda} \\ \frac{\alpha B}{\omega} &= \lambda \\ \dot{\lambda} &= \lambda(-r-p+p+\theta) = -\lambda(r-\theta) \\ \dot{c} &= c(r-\theta) \end{aligned}$$

with the wealth accumulation constraint.

Under the guess we can show that

$$c = \eta w, \quad \omega = \alpha B \eta w$$

with

$$\eta = \frac{p + \theta}{p\alpha B + 1}$$

Also, under the guess, we can compute the value $V(z)$ as:

$$V(z) = \text{constant} + \frac{1 + p\alpha B}{\theta + p} \ln z$$

(see the "Derivation of the discounted utility along the optimal path" above). The guess is verified therefore for³⁸

$$B = \frac{1 + p\alpha B}{\theta + p}$$

that is

$$B = \frac{1}{\theta + p(1 - \alpha)}$$

We conclude that:

$$\eta = \frac{p + \theta}{p\alpha \frac{1}{\theta + p(1 - \alpha)} + 1} = \theta + p(1 - \alpha)$$

and so

$$c = (\theta + p(1 - \alpha)) w, \quad \omega = \alpha w$$

³⁸Naturally we also need to require constant = A .

4.1.2 Appendix B: On the mechanisms possibly underlying a Pareto distribution of wealth

Various stochastic processes for individual wealth are known to aggregate into a Pareto distribution of wealth in the population; see Sornette (2000) for a technical review and Chipman (1976) for a careful and outstanding account of the historical contributions of this subject; see also Levy (2003).

One such process is exemplified here; its mathematical formulation first appears in Cantelli (1921).³⁹ Suppose a variable determining wealth (e.g., talent, age), which we denote α , is exponentially distributed. That is the number of people with $\alpha = \alpha_0$ is

$$N(\alpha_0) = pe^{-p\alpha_0}$$

Suppose wealth increases exponentially with α :

$$w = ae^{g\alpha}, \quad a > 0, \quad g \geq 0 \quad (55)$$

Therefore, we can solve for $\alpha = g^{-1} \ln \frac{w}{a}$, operate a change of variables and express the distribution of wealth as

$$N(w) = N\left(g^{-1} \ln \frac{w}{a}\right) \frac{d\alpha}{dw}$$

that is,

$$N(w) = \frac{p}{g} a^{\frac{p}{g}} w^{-\left(\frac{p}{g}+1\right)}$$

This is a Pareto distribution with the exponent $\frac{p}{g}$.⁴⁰

The underlying mechanism which makes wealth Pareto distributed in our basic model is a similar one in which the factor α is represented by age. This is clearly illustrated by considering the simple economy with no bequests. At any time t , in this economy, the distribution of the population by age $t - s$ implied by the demographic structure of the economy is in fact

$$N(t - s) = pe^{-p(t-s)}$$

Moreover, abstracting from the complications of inheritance, each optimal consumption-savings choices imply a wealth accumulation process results in wealth increasing exponentially with age.

³⁹See also Fermi (1949)'s study of cosmic rays.

⁴⁰A notable literature appeared in Italian in the first decades of the twentieth century which studies the wealth distribution resulting from different assumptions regarding the distribution of the generating factor we called α and on the functional dependence of wealth on this factor; see Chipman (1976) for a detailed discussion of these contributions.

4.1.3 Appendix C: On the basic PDE and its solution by the "method of characteristics"

We illustrate in this Appendix the "method of characteristics" for the solution of partial differential equation (PDE's) by applying to a linear PDE with variable coefficients, a simple form of the PDE we solve in the paper. Consider the following PDE:

$$\frac{\partial f}{\partial t} = -af - bz \frac{\partial f}{\partial z} \quad (56)$$

with initial condition

$$f(z, 0) = h(z)$$

Suppose first of all that the PDE is to be solved for $z \in \mathfrak{R}$, that is, that there is no boundary condition. The Method of Characteristics (see e.g., Farlow (1982), Ch. 27) requires solving the PDE in the characteristic space, (τ, t) , implicitly constructed as follows:

$$\frac{dz}{d\tau} = bz, \quad \frac{dt}{d\tau} = 1$$

that is,

$$z(\tau) = c_1 e^{-b\tau}, \quad t(\tau) = \tau + c_2 \quad (57)$$

Let $z(0) = m$ and $t(0) = 0$, so that $c_1 = m$ and $c_2 = 0$. This construction has the property that the chain rule

$$\frac{df}{d\tau} = \frac{\partial f}{\partial z} \frac{\partial z}{\partial \tau} + \frac{\partial f}{\partial t} \frac{\partial t}{\partial \tau}$$

and (56) imply

$$\frac{df}{d\tau} = -af \quad (58)$$

a simple ordinary differential equation. The initial condition in characteristic space is $f(m, 0) = h(m)$. The differential equation, together with the initial condition has solution

$$f(z(\tau), \tau) = h(m) e^{-a\tau}$$

Substituting back into the original space (z, t) , using (57):

$$f(z, t) = h(z e^{-bt}) e^{-at} \quad (59)$$

In words: the density on z at time t is the same density that at time 0 was on $z e^{-bt}$ dampened at a rate a .

Suppose now that the PDE is to be solved for $z \geq \underline{z}$, and that there is a boundary condition

$$f(\underline{z}, t) = B,$$

The Method of Characteristics applies to this class of problems, boundary value problems, as follows (see e.g., Hood (2003) and Strikwerda (2004), Ch. 1.2). The characteristic space is split along the characteristic $z = \underline{z}e^{bt}$. In particular, for $z \geq \underline{z}e^{bt}$ the solution to the PDE is determined by the initial condition, and

$$f(z, t) = h(z e^{-bt}) e^{-at}$$

For $z < \underline{z}e^{bt}$ the solution is instead determined by the boundary condition through the inverse transformation $\tau(z, y) = \ln \frac{z}{y} \frac{1}{b}$ and

$$f(z, t) = B \frac{1}{b} \left(\frac{z}{\underline{z}} \right)^{\frac{a}{b}}$$

Summarizing, the solution to the boundary value problem is:

$$f(z, t) = \begin{cases} B \frac{1}{b} \left(\frac{z}{\underline{z}} \right)^{\frac{a}{b}} & \text{for } z < \underline{z}e^{bt} \\ h(z e^{-bt}) e^{-at} & \text{for } z \geq \underline{z}e^{bt} \end{cases} \quad (60)$$

4.1.4 Appendix D: On Volterra-Fredholm integral equations of the second type

In this Appendix we report some results for the class of integral equations that we study in the paper. We consider Volterra-Fredholm integral equations of the second type with separable kernel:

$$f(z) = h(z) + \lambda \int_a^{\sigma(z)} K(y)H(z)f(y)dy$$

where the real maps h , σ , K , and H are continuously differentiable. It is convenient to study the following equivalent equation:

$$f(z) = h(z) + \lambda \int_a^{\infty} \tilde{K}(z, y)H(z)f(y)dy, \quad \tilde{K}(z, y) = K(y)I_{[a, \sigma(z)]}(z, y) \quad (61)$$

where $I_{[a, \sigma(z)]}(z, y)$ is the indicator function of the interval $[a, \sigma(z)]$, $I_{[a, \sigma(z)]}(y) = \begin{cases} 1 & \text{for } y \in [a, \sigma(z)] \\ 0 & \text{otherwise} \end{cases}$. Note that $\tilde{K}(z, y)$ is not continuous. The theory of Volterra-Fredholm integral equations is, however, developed for square integrable kernels (see Tricomi (1957)), a condition which is obviously satisfied by $\tilde{K}(z, y)H(z)$. For the uniqueness of such solutions (excluding solutions that are zero almost everywhere) see Tricomi (1957), p. 10 and Chapter II and also p.63.

A simple explicit solution is reported by Polyanin-Manzhurov (1998), Ch. 2.1-7 (equation 50), for the following integral equation:

$$f(z) = h(z) + \lambda \int_a^z y^{\alpha_1} z^{\alpha_2} f(y)dy, \quad \text{for } \alpha_1 + \alpha_2 = -1$$

It corresponds to a special case of (61) in which:

$$\sigma(z) = z, \quad \tilde{K}(z, y) = K(y) = y^{\alpha_1}, \quad H(z) = z^{-\alpha_1-1}$$

Its solution is:

$$f(z) = h(z) + \int_a^z R(z, y)h(y)dy, \quad \text{for } R(z, y) = az^{\alpha_2-\lambda}y^{\alpha_1+\lambda}$$