

## Optimal Taxation and Debt with Uninsurable Risks to Human Capital Accumulation

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**Abstract:** We consider an economy where individuals face uninsurable risks to their human capital accumulation and study the problem of determining the optimal level of linear taxes on capital and labor income together with the optimal path of the debt level. We show both analytically and numerically that in the presence of such risks it is beneficial to tax both labor and capital income and to have positive government debt.

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Key words: incomplete markets, Ramsey equilibrium, optimal taxation, optimal public debt

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# 1 Introduction

Human capital is an important component of wealth both at the individual and aggregate level, and its role has been investigated in various fields in economics. In public finance, Jones, Manuelli and Rossi (1997) show that the zero-capital-tax result of Chamley (1986) and Judd (1985)<sup>1</sup> can be strengthened if human capital accumulation is explicitly taken into account. Specifically, they demonstrate that, in a deterministic economy with human capital accumulation, in the long run not only capital but also labor income taxes should be zero, hence the government must accumulate wealth to finance its expenditure.

In this paper we show that the introduction of uninsurable idiosyncratic shocks to the accumulation of human capital drastically changes the result of Jones, Manuelli and Rossi (1997), as it becomes optimal for the government to tax both labor and capital income even in the long run. Thus, our analysis shows how the interaction between market incompleteness and human capital accumulation provides a novel justification for a positive tax rate on capital. The desirability of taxing both capital and labor income implies then a beneficial role of government debt, and so our theory provides also a rationale for the presence of a positive level of government debt, in line with observed evidence.

Our model builds on that of Krebs (2003), who augmented the endogenous growth model of Jones and Manuelli (1990) with uninsurable idiosyncratic risks to human capital accumulation. We assume that there is a unit measure of infinitely-lived individuals, who can invest in three types of assets: government bonds, physical capital, and human capital. The first two assets are risk-free while human capital is risky and there are no insurance markets where this risk can be hedged. As a result, individuals face uninsurable fluctuations in their labor income.

In this environment we study a Ramsey taxation problem, where linear taxes on labor and capital income are chosen so as to maximize a weighted average of individuals' lifetime utility. The model considered turns out to be quite tractable and allows us to derive both analytic and quantitative properties of the solution of the Ramsey problem. It also allows us to maximize the average lifetime utility of individuals, rather than the average of their utility at the steady state (as common in the earlier literature), and thus to take into account also the transition to the steady state. A common assumption in the previous literature is that the social planner only maximizes

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<sup>1</sup>Judd and Chamley find that the optimal tax rate on capital is zero in the long run in a deterministic economy with infinitely lived households. This result has been extended by Zhu (1992) to a representative-agent economy with aggregate shocks, and by Karantounias (2013) to economies with more general, recursive preferences. The result by Atkinson and Stiglitz (1976) on uniform commodity taxation theorem provides then a condition under which the optimal tax rate on capital is always zero (not just in the steady state).

the average utility at the steady state, thus the transition is ignored.

Our theoretical findings are summarized as follows. First, taxing labor income is beneficial because it reduces the risk associated with labor income. Indeed, if the government is required to have a balanced budget in every period, the optimal tax rate on labor income is positive and the optimal tax rate on capital income is negative, as long as government purchases are small enough. It is worth noting that at a competitive equilibrium of our model without taxes the ratio of physical-to-human capital is higher than at the first-best allocation (where idiosyncratic shocks are fully hedged), thus there is “over-accumulation” of physical capital.<sup>2</sup> Still, our result shows this does not mean that capital income should be taxed, on the contrary it should be subsidized under the balanced budget requirement.

Our second result shows the benefits of capital income taxation and government debt. To better understand it, it is useful to relate it to the finding of Chamley and Judd. These authors showed, in the deterministic environment they considered, that at an optimal steady state the rate of return earned by the private sector on its savings, given by the after-tax return on (physical) capital, should equal the cost of funds for the government, given by the before-tax return. Hence the zero capital tax rate. In our model we prove that a similar condition should hold.<sup>3</sup> However, with risky capital the expected rate of return for the private sector is a weighted average between the after-tax returns on human and physical capital. Since the first one is risky and the second safe, this average is higher than the after-tax return on physical capital, while the return relevant for the government is still the before-tax rate on physical capital. Thus, in order for the private sector and the government to earn the same rate of return, the after-tax rate on physical capital must be smaller than its before-tax rate, and hence the capital tax rate must be strictly positive in the long run. Since it is beneficial to tax both labor and capital income in the long run, the optimal amount of government debt is positive, as long as public expenditure is small enough.

To evaluate the quantitative importance of our findings, we calibrate our model to the U.S. economy. In particular, we set the variance of the shock to human capital so as to match Meghir and Pistaferri’s (2004) estimate of the variance of the permanent shock to labor income and consider values of the agents’ coefficient of relative risk aversion between one and nine. We then numerically investigate the properties of the Ramsey equilibrium, finding that the capital tax rate at the Ramsey steady state is sizable: it is about 10 percent when risk aversion is low (CRRA is one) and exceeds

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<sup>2</sup>See Gottardi, Kajii and Nakajima (2011) for a proof. The same property holds in the standard incomplete-market macroeconomic model (see Aiyagari (1994)).

<sup>3</sup>Strictly speaking, when the elasticity of intertemporal substitution is different from one a correction term is also present, capturing the effect of public debt on the saving rate.

30 percent when it is relatively high (CRRA is nine). The government debt to output ratio at the Ramsey steady state is -100 percent with low risk aversion, and close to +200 percent with high risk aversion. These findings show that the optimal policy is not very far from our estimate of the current U.S. fiscal policy, so that the welfare gain of adopting the optimal policy appears to be relatively modest, and much smaller, for instance, from the one obtained in the deterministic model by Jones, Manuelli, and Rossi (1993).

The idea that uninsurable labor income risks may justify taxing capital income is not new. In the framework of a standard incomplete markets macroeconomic model, where the labor productivity of each individual follows an exogenously specified stochastic process, Aiyagari (1995) also finds that the tax on capital must be positive at the steady state solution of the Ramsey problem. However, in the environment considered by Aiyagari (1995), with no human capital accumulation and endogenous government expenditure, the tax rate on capital must be positive for a steady state to exist. One may then question to what extent the standard incomplete markets model provides a clear support to the view that uninsurable labor income shocks justify capital income taxation.<sup>4</sup> In our model in contrast, with human capital accumulation together with uninsurable income shocks, the existence of a steady state imposes no real restriction on the value of the tax rate on capital and the optimality of a positive tax rate is primarily determined by the comparison of costs and benefits of the tax and debt. A partially different line of argument is pursued by Conesa, Kitao and Krueger (2009) who consider a quantitative overlapping-generations model with uninsurable labor income shocks, allowing also for nonlinear labor income taxes. They find that the optimal capital income tax rate is positive and significant, but the desirability of capital income taxation in their model is primarily due to the effects of the life cycle on agents' behavior and the absence of age-dependent labor income taxes, more than to market incompleteness.

Finally, regarding the desirability of government debt, we should mention a related result obtained by Aiyagari and McGrattan (1998) in a model with uninsurable labor income shocks. However, differently from us they consider an environment where borrowing constraints are binding, they derive the optimal policy as solution of the problem of maximizing the agents' steady-state average utility and restrict the labor and capital tax rates to be identical. Because in particular of the latter restriction, the benefits of higher taxes (on labor as well as capital) cannot be separated from those of higher debt.

The rest of the paper is organized as follows. In Section 2, the economy is described, and the benchmark equilibrium without taxes is characterized. Section 3 considers the dynamic Ramsey problem and derives the main theoretical results on the properties of the optimal levels of taxes and

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<sup>4</sup>See also İmrohoroğlu (1998), Domeij and Heathcote (2004) and Açıkgöz (2013) for other work along these lines.

government debt. Section 4 describes then the numerical results and Section 5 concludes. Most of the proofs are collected in the Appendix<sup>5</sup>.

## 2 The Economy

We consider a competitive economy subject to idiosyncratic shocks. Time is discrete and indexed by  $t = 0, 1, 2, \dots$ . The economy consists of consumers, firms producing a homogeneous consumption good using physical capital and human capital as inputs, and the government collecting taxes and issuing debt.

### 2.1 Consumers

There is a continuum of infinitely lived consumers. In every period each individual is endowed with one unit of raw labor, which he supplies inelastically, and can use his revenue to consume the consumption good and invest in three kinds of assets: a risk-free bond, physical capital and human capital. His level of human capital determines the “efficiency units” of his labor.

Each individual  $i \in [0, 1]$  has Epstein-Zin-Weil preferences over random sequences of consumption, which are defined recursively by

$$u_{i,t} = \left\{ (1 - \beta)(c_{i,t})^{1-\frac{1}{\psi}} + \beta [E_t(u_{i,t+1})^{1-\gamma}]^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right\}^{\frac{\psi}{\psi-1}}, \quad t = 0, 1, \dots \quad (1)$$

where  $u_{i,t}$  is the intertemporal utility of individual  $i$  evaluated at date  $t$ ,  $E_t$  is the conditional expectation operator at time  $t$ ,  $c_{i,t}$  is his/her consumption in period  $t$ ,  $\beta \in (0, 1)$  is the discount factor,  $\psi$  is the elasticity of intertemporal substitution, and  $\gamma$  is the coefficient of relative risk aversion.

Let  $b_{i,t-1}$ ,  $k_{i,t-1}$  and  $h_{i,t-1}$  denote, respectively, the quantities of risk-free bond, physical capital, and human capital that individual  $i$  holds at the end of period  $t - 1$ . To capture the idea that labor income is subject to uninsurable idiosyncratic shocks, we assume that, for each  $i, t$ , the human capital of individual  $i$  is affected by a random shock,  $\theta_{i,t}$  at the beginning of period  $t$ . Hence the actual amount of human capital available to individual  $i$  is  $\theta_{i,t}h_{i,t-1}$ .

Each consumer  $i$  is initially endowed with a non negative amount  $b_{i,-1}$ ,  $k_{i,-1}$  and  $h_{i,-1}$  of riskless bond, physical and human capital. Let then  $\nu_{k,i,t}$  and  $\nu_{h,i,t}$  denote the units of the consumption good invested in, respectively, physical and human capital by individual  $i$  in period  $t$ . The amount of the two types of capital held at the end of period  $t$ , for  $t = 0, 1, \dots$ , is then equal to the amount

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<sup>5</sup> Available online at <http://apps.eui.eu/Personal/Gottardi/>.

held at the beginning of the period, less the depreciation, plus the investment:

$$k_{i,t} = \iota_{k,i,t} + (1 - \delta_k)k_{i,t-1} \quad (2)$$

$$h_{i,t} = \iota_{h,i,t} + (1 - \delta_h)\theta_{i,t}h_{i,t-1} \quad (3)$$

where  $\delta_k$  and  $\delta_h$  are the depreciation rates of physical and human capital, respectively.

We assume that the variables  $\theta_{i,t}$ ,  $i \in [0, 1]$ ,  $t = 0, \dots$ , are identically and independently distributed across individuals and across periods, with unit mean. We further assume that the law of large number applies, so that the aggregate stock of human capital at the beginning of each period  $t$  is not random, that is, the following relation holds with probability one:

$$\int_0^1 \theta_{i,t}h_{i,t-1} di = \int_0^1 h_{i,t-1} di = H_{t-1}. \quad (4)$$

The idiosyncratic shocks  $\theta_{i,t}$  are the only sources of uncertainty. Hence there is no aggregate uncertainty in the economy and the rental rates of the two production factors are deterministic.

Let  $r_t$  denote the rental rate of physical capital and  $w_t$  the wage rate. Both labor and capital income are subject to linear taxes at the rates  $\tau_{h,t}$  and  $\tau_{k,t}$  at each date  $t$ . In what follows it is convenient to use the notation  $\tilde{r}_t$  and  $\tilde{w}_t$  for the after tax prices,  $r_t(1 - \tau_{k,t})$  and  $w_t(1 - \tau_{h,t})$ .

The flow budget constraint of individual  $i$  is given by, for each  $t = 0, 1, \dots$ ,

$$c_{i,t} + k_{i,t} + b_{i,t} + h_{i,t} = R_{k,t}k_{i,t-1} + R_{k,t}b_{i,t-1} + R_{h,t}\theta_{i,t}h_{i,t-1} \quad (5)$$

where  $R_{k,t} = 1 - \delta_k + \tilde{r}_t$ , and  $R_{h,t} = 1 - \delta_h + \tilde{w}_t$ . Since the (after tax) rate of return on physical capital  $R_{k,t}$  is non random, in equilibrium the rate of return on risk-free bonds must be the same.

It is convenient to use  $x_{i,t}$  to denote the term on the right hand side of (5), indicating the total wealth of individual  $i$  at the beginning of period  $t$  after the time  $t$  shock  $\theta_{i,t}$  has been realized. Individuals may borrow, that is,  $b_{i,t}$  can be negative, while the holdings of capital are required to be non-negative:  $k_{i,t} \geq 0$  and  $h_{i,t} \geq 0$  for all  $i, t$ . The amount of borrowing is restricted by the natural debt limit, that prevents consumers from engaging in Ponzi schemes and in this environment (where the only source of future income is the revenue from the consumers' accumulated human and physical capital) takes the following form:

$$x_{i,t} \geq 0, \quad (6)$$

for all periods  $t = 1, \dots$  and all contingencies.

To sum up, given the initial wealth  $x_{i,0} > 0$  and a sequence of after tax prices  $\{\tilde{r}_t, \tilde{w}_t\}_{t=1}^\infty$ , each individual  $i$  maximizes his lifetime utility  $u_{i,0}$ , defined by (1) subject to the flow budget constraints (5) and the debt limit (6).

The individual's decision depends on the history of idiosyncratic shocks affecting him. Thanks to the specification of the utility function (1) and the assumption that shocks are i.i.d., a tractable characterization of the utility maximizing choices is however possible.

First, it is convenient to rewrite equation (5) as follows:

$$x_{i,t+1} = (1 - \eta_{c,i,t}) \{R_{k,t+1}(1 - \eta_{h,i,t}) + R_{h,t+1}\theta_{i,t+1}\eta_{h,i,t}\} x_{i,t} \quad (7)$$

where

$$\eta_{c,i,t} \equiv \frac{c_{i,t}}{x_{i,t}}, \quad \eta_{h,i,t} \equiv \frac{h_{i,t}}{b_{i,t} + k_{i,t} + h_{i,t}}$$

with initial condition  $x_{i,0} > 0$ . The individual optimization problem can then be equivalently written as a problem of choosing a sequence of the rate of consumption out of his wealth,  $\eta_{c,i,t}$ , and of the portfolio composition between human capital and riskless assets (physical capital and risk-free bond),  $(\eta_{h,i,t}, 1 - \eta_{h,i,t})$  for every  $t = 0, 1, \dots$ , given  $x_{i,0}$ .

Define the certainty-equivalent rate of return  $\rho$  associated with the after-tax rental rate  $\tilde{r}$  and after-tax wage rate  $\tilde{w}$  as follows:

$$\rho(\tilde{r}, \tilde{w}, \eta_h) \equiv \left\{ E \left( (1 - \delta_k + \tilde{r})(1 - \eta_h) + \theta(1 - \delta_h + \tilde{w})\eta_h \right)^{1-\gamma} \right\}^{\frac{1}{1-\gamma}}. \quad (8)$$

Given the specification of the agents' utility and income, it can be shown that the optimal portfolio at any date, given the prevailing after-tax rates  $\tilde{r}$  and  $\tilde{w}$ , is obtained as a solution to the static problem of maximizing  $\rho(\tilde{r}, \tilde{w}, \eta_h)$  with respect to  $\eta_h$ , independently of all the other choice variables. Given this, it is straightforward to verify that the following simple characterization of the solutions of the individual choice problem obtains:

**Lemma 1.** *Given  $\{\tilde{r}_t, \tilde{w}_t\}_{t=1}^{\infty}$  and  $x_{i,0}$ , for any individual  $i$  a utility maximizing sequence of portfolio compositions and rates of consumption is characterized by the following rule: for each  $t = 0, 1, \dots$ ,*

$$\rho_{t+1} = \max_{\eta'_h \geq 0} \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1}, \eta'_h), \quad (9)$$

$$\eta_{h,t} = \arg \max_{\eta'_h \geq 0} \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1}, \eta'_h), \quad (10)$$

$$\eta_{c,t} = \left\{ 1 + \sum_{s=0}^{\infty} \prod_{j=0}^s \left( \beta^{\psi} \rho_{t+1+j}^{\psi-1} \right) \right\}^{-1}. \quad (11)$$

Moreover, the time  $t$  intertemporal utility level is given by

$$u_{i,t} = v_t x_{i,t},$$

where  $x_{i,t}$  satisfies (7) and  $v_t$  satisfies the recursive expression:

$$v_t^{\psi-1} = (1 - \beta)^{\psi} + \beta^{\psi} \rho_{t+1}^{\psi-1} v_{t+1}^{\psi-1}, \quad (12)$$

whose solution is

$$v_t = (1 - \beta)^{\frac{\psi}{\psi-1}} \left\{ 1 + \sum_{s=0}^{\infty} \prod_{j=0}^s \left( \beta^\psi \rho_{t+1+j}^{\psi-1} \right) \right\}^{\frac{1}{\psi-1}}. \quad (13)$$

Since the expressions in (10) and (11) are independent of  $i$ , the result implies that all the individuals in the economy choose the same rate of consumption,  $\eta_{c,t}$ , and the same portfolio,  $\eta_{h,t}$ , in each period  $t$ . The heterogeneity among individuals appears in their level of wealth and hence in their utility level, given by wealth times a common constant  $v_t$ .

Comparing (11) and (13) we see that the utility level per unit of wealth  $v_t$  and the consumption share  $\eta_{c,t}$  at any date  $t$  are related as follows:

$$\eta_{c,t} = (1 - \beta)^\psi v_t^{1-\psi}. \quad (14)$$

Since  $\rho(\cdot)$  is a concave function of  $\eta_h$ , an interior solution of (9) is characterized by the first order conditions:

$$\begin{aligned} \Phi(\tilde{r}, \tilde{w}, \eta_h) \equiv E \left[ \left\{ (1 - \delta_k + \tilde{r})(1 - \eta_h) + \theta(1 - \delta_h + \tilde{w})\eta_h \right\}^{-\gamma} \right. \\ \left. \times \left\{ \theta(1 - \delta_h + \tilde{w}) - (1 - \delta_k + \tilde{r}) \right\} \right] = 0. \end{aligned} \quad (15)$$

We shall assume throughout the analysis that the derivatives of the function  $\Phi : \mathbb{R}_+^3 \rightarrow \mathbb{R}$ , defined in equation (15), exhibit the following properties:

**Assumption 1.** *The derivatives of  $\Phi(\cdot)$ , evaluated at  $\Phi = 0$ , satisfy:*

$$\frac{\partial \Phi}{\partial \tilde{r}} < 0, \quad \text{and} \quad \frac{\partial \Phi}{\partial \tilde{w}} > 0.$$

It can be verified that these properties are satisfied when  $\gamma \leq 1$ . When  $\gamma > 1$ , they hold under appropriate restrictions on the distribution of  $\theta_i$ . The concavity of  $\rho(\cdot)$  then implies that  $\frac{\partial \Phi}{\partial \eta_h} < 0$ . These properties ensure that the consumers' optimal portfolio choice displays the 'normal' comparative statics properties:  $\partial \eta_h / \partial \tilde{r} < 0$  and  $\partial \eta_h / \partial \tilde{w} > 0$ .

## 2.2 Firms

All firms have identical production technology, described by a Cobb-Douglas production function, so we can proceed as if there is a single representative firm. Letting  $K_{t-1}$  and  $H_{t-1}$  denote, respectively, the aggregate stock of physical and human capital used by firms at the beginning of period  $t$ , the aggregate amount of output produced in period  $t$  is:

$$Y_t = F(K_{t-1}, H_{t-1}) = AK_{t-1}^\alpha H_{t-1}^{1-\alpha}, \quad (16)$$

where  $Y_t$  is the aggregate level of output and  $A$  is a constant. The profit maximization condition requires that the marginal productivity of the two factors equal their before-tax rental rates

$$r_t = \frac{\partial F(K_{t-1}, H_{t-1})}{\partial K_{t-1}} \equiv F_{k,t}, \quad w_t = \frac{\partial F(K_{t-1}, H_{t-1})}{\partial H_{t-1}} \equiv F_{h,t}. \quad (17)$$

### 2.3 Government

The government purchases an amount of output,  $G_t$ , in each period  $t$ , financed by collecting taxes and issuing debt. Let  $B_{t-1}$  be the government debt outstanding at the beginning of period  $t$ . The flow budget constraint of the government at any date  $t$  is

$$B_t + F(K_{t-1}, H_{t-1}) - \tilde{r}_t K_{t-1} - \tilde{w}_t H_{t-1} = G_t + (1 - \delta_k + \tilde{r}_t) B_{t-1}, \quad (18)$$

where we used  $\tilde{r}_t$ ,  $\tilde{w}_t$  and the linear homogeneity of the production function  $F(K, H)$  to rewrite the tax revenue  $\tau_{k,t} r_t K_{t-1} + \tau_{h,t} w_t H_{t-1}$  and the initial stock of debt  $B_{-1}$  is given:  $B_{-1} = \int_0^1 b_{i,-1} di$ .

For a given sequence of the aggregate stocks of physical and human capital and prices  $\{K_t, H_t, r_t, w_t\}_{t=0}^\infty$ , a fiscal policy  $\{\tilde{r}_t, \tilde{w}_t, B_t\}_{t=0}^\infty$  is said to be feasible if the flow budget constraint (18) is satisfied for every  $t = 0, 1, \dots$ , and

$$\lim_{t \rightarrow \infty} \left[ \prod_{j=1}^t (1 - \delta_k + \tilde{r}_j)^{-1} \right] B_t = 0. \quad (19)$$

### 2.4 Competitive equilibrium

Given a sequence of government purchases,  $\{G_t\}_{t=0}^\infty$  and a fiscal policy  $\{\tilde{r}_t, \tilde{w}_t, B_t\}_{t=0}^\infty$ , a *competitive equilibrium* is defined by a price system  $\{r_t, w_t\}_{t=0}^\infty$  and a collection of stochastic processes  $\{c_{i,t}, x_{i,t}, b_{i,t}, k_{i,t}, h_{i,t}\}_{t=0}^\infty$ ,  $i \in [0, 1]$ , adapted to the filtration generated by the process of idiosyncratic shocks  $\{\theta_{i,t}\}_{t=0}^\infty$ , such that: (a) for each  $i$ ,  $\{c_{i,t}, x_{i,t}, b_{i,t}, k_{i,t}, h_{i,t}\}_{t=0}^\infty$  solves the utility maximization problem of agent  $i$ , subject to (5) and (6), given prices, the fiscal policy and the initial endowment  $b_{i,-1}$ ,  $k_{i,-1}$ ,  $h_{i,-1}$ ; (b) firms maximize profits, that is, (17) holds for all  $t \geq 0$ , with  $K_{t-1} = \int_0^1 k_{i,t-1} di$  and  $H_{t-1}$  satisfying (4); (c) all markets clear:

$$\begin{aligned} C_t + G_t + K_t + H_t &= (1 - \delta_k) K_{t-1} + (1 - \delta_h) H_{t-1} + F(K_{t-1}, H_{t-1}), \\ B_t &= \int_0^1 b_{i,t} di \end{aligned} \quad (20)$$

where  $C_t = \int_0^1 c_{i,t} di$ ; (d) the government policy is feasible, that is (18) and (19) hold.

Let  $X_t$  denote the average amount of wealth at the beginning of period  $t$ :  $X_t \equiv \int_0^1 x_{i,t} di$ . Recalling that, as shown in Lemma 1, the consumers' optimum is characterized by the sequence  $\{\eta_{c,t}, \eta_{h,t}\}_{t=0}^\infty$ , independent of  $i$ ,  $X_t$  evolves as

$$X_{t+1} = R_{x,t+1} (1 - \eta_{c,t}) X_t, \quad t = 0, 1, 2, \dots \quad (21)$$

where  $R_{x,t+1}$  is the equilibrium average rate of return of individual portfolios: for  $t = 0, 1, 2, \dots$

$$R_{x,t+1} \equiv (1 - \delta_k + \tilde{r}_t)(1 - \eta_{h,t}) + (1 - \delta_h + \tilde{w}_t)\eta_{h,t}. \quad (22)$$

Given  $X_t$ , aggregate consumption, physical and human capital are given by

$$C_t = \eta_{c,t}X_t, \quad (23)$$

$$K_t = (1 - \eta_{c,t})(1 - \eta_{h,t})X_t - B_t, \quad (24)$$

$$H_t = (1 - \eta_{c,t})\eta_{h,t}X_t. \quad (25)$$

Hence the aggregate dynamics of a competitive equilibrium is simply determined by the sequence  $\{\eta_{c,t}, \eta_{h,t}\}_{t=0}^{\infty}$  and the path of average wealth  $X_t$ .

## 2.5 Benchmark equilibrium with no taxes

As a benchmark, let us consider the situation where the government does not purchase goods, and does not issue debt nor impose any taxes:

$$G_t = B_t = 0, \quad r_t - \tilde{r}_t = 0, \quad w_t - \tilde{w}_t = 0 \quad \text{for all } t \geq 0, \quad b_{i,-1} = 0, \quad \text{for all } i \in [0, 1]. \quad (26)$$

In this case, the competitive equilibrium has a very simple structure. The aggregate economy is always on a balanced growth path, although each individual's consumption fluctuates stochastically over time.

To see this, notice that, using (26), (17) and the market clearing conditions for physical and human capital, the first order conditions for the consumers' optimal portfolio choice (15) reduce to

$$\Phi [F_k(1 - \eta_{h,t}, \eta_{h,t}), F_h(1 - \eta_{h,t}, \eta_{h,t}), \eta_{h,t}] = 0, \quad (27)$$

for every  $t = 0, 1, 2, \dots$ . It is then immediate to verify<sup>6</sup> that there exists a unique  $\hat{\eta}_h \in (0, 1)$  satisfying (27), which implies that  $\eta_{h,t} = \hat{\eta}_h$  must hold for every  $t$ .

Set  $\hat{F}_k = F_k(1 - \hat{\eta}_h, \hat{\eta}_h)$ ,  $\hat{F}_h = F_h(1 - \hat{\eta}_h, \hat{\eta}_h)$ , and

$$\hat{\rho} = \rho \left( \hat{F}_k, \hat{F}_h, \hat{\eta}_h \right). \quad (28)$$

The argument above together with Lemma 1 yield the following characterization of the equilibria in this benchmark case:<sup>7</sup>

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<sup>6</sup>From (15) we have  $F_k(1, 0) = F_h(0, 1) = 0$ ,  $F_k(0, 1) = F_h(1, 0) = +\infty$ , and  $\lim_{\eta_h \rightarrow 0} F_h(1 - \eta_h, \eta_h)h = \lim_{\eta_h \rightarrow 1} F_k(1 - \eta_h, \eta_h)(1 - \eta_h) = 0$ . Furthermore, under Assumption 1,  $\frac{\partial}{\partial \eta_h} \Phi [F_k(1 - \eta_h, \eta_h), F_h(1 - \eta_h, \eta_h), \eta_h] < 0$  whenever  $\Phi = 0$ . The claim then follows.

<sup>7</sup>Krebs (2003) derived analogous properties in a similar environment.

**Proposition 2.** *Suppose that Assumption 1 holds. If*

$$\beta^\psi \hat{\rho}^{\psi-1} < 1,$$

*with no government intervention - i.e., under (26) - a unique competitive equilibrium exists, characterized by  $\hat{\eta}_h$  and  $\hat{\eta}_c \equiv 1 - \beta^\psi \hat{\rho}^{\psi-1}$ . Thus the aggregate variables  $C_t$ ,  $K_t$ ,  $H_t$ , and  $X_t$  all grow at the same rate*

$$\hat{g}_x = (1 - \hat{\eta}_c) \hat{R}_x$$

where

$$\hat{R}_x = (1 - \delta_k + \hat{F}_k)(1 - \hat{\eta}_h) + (1 - \delta_h + \hat{F}_h)\hat{\eta}_h,$$

and

$$\hat{v} \equiv \left[ \frac{(1 - \beta)^\psi}{1 - \beta^\psi \hat{\rho}^{\psi-1}} \right]^{\frac{1}{\psi-1}}.$$

In what follows we refer to this equilibrium without government purchases or taxes as the *benchmark equilibrium*, and use a hat ( $\hat{\cdot}$ ) to denote the value of a variable at this equilibrium.

### 3 Optimal taxation and debt

In this section we study the dynamic Ramsey problem where the optimal tax and debt policy in our environment are determined. As is well known from the work of Chamley (1986) and Judd (1985), when markets are complete the optimal tax rate on capital income is zero in the steady state. Furthermore, when there is also human capital accumulation, Jones, Manuelli, and Rossi (1997) have shown that both labor and capital income tax should be zero in the long run and hence, with positive government purchases, public debt should be negative. Here we demonstrate that uninsurable risks in human capital accumulation significantly change the nature of optimal taxes. The presence of such risks makes both labor and capital income taxation beneficial, which, in turn, implies that the optimal amount of government debt is positive as long as government purchases are sufficiently small.

More precisely, the *Ramsey problem* consists in finding the fiscal policy  $\{\tilde{r}_t, \tilde{w}_t, B_t\}_{t=0}^\infty$ , satisfying (18) and (19), that maximizes consumers' welfare at the associated competitive equilibrium, as defined in Section 2.4, for a given policy determining the level of government purchases  $\{G_t\}_{t=0}^\infty$ . The resulting equilibrium is then denoted the *Ramsey equilibrium*. As is standard in the literature, we assume that the tax rates, or equivalently the after tax prices, in the initial period are exogenously fixed:

$$\tilde{r}_0 = \bar{r}_0, \quad \text{and} \quad \tilde{w}_0 = \bar{w}_0. \tag{29}$$

We take as social welfare function a weighted average of the lifetime utility of individuals:  $\int_0^1 \lambda_i u_{i,0} di$ , with  $\lambda_i \in (0, 1)$  for each individual  $i \in [0, 1]$ . By Lemma 1, we have  $u_{i,0} = v_0 x_{i,0}$ , and therefore

$$\int_0^1 \lambda_i u_{i,0} di = v_0 \int_0^1 \lambda_i x_{i,0} di = v_0 \left\{ (1 - \delta_k + \tilde{r}_0) \int_0^1 \lambda_i (k_{i,-1} + b_{i,-1}) di + (1 - \delta_h + \tilde{w}_0) \int_0^1 \lambda_i \theta_{i,0} h_{i,-1} di \right\}.$$

Given the initial tax rates (29), the terms in the curly braces are determined independently of the fiscal policy chosen by the government. Thus the government's objective reduces to maximizing the utility coefficient:

$$v_0 = (1 - \beta)^{\frac{\psi}{\psi-1}} \left\{ 1 + \sum_{t=0}^{\infty} \prod_{j=0}^t \left( \beta^\psi \rho_{1+j}^{\psi-1} \right) \right\}^{\frac{1}{\psi-1}} \quad (30)$$

Note that (30) implies that  $v_0$  is strictly increasing in  $\rho_t$  for all  $t$ , regardless of the value of  $\psi > 0$ . We should stress that in the Ramsey problem as specified above we are looking for a sequence of tax rates and debt levels which may vary over time and are such to maximize the lifetime utility of agents, not just their steady state utility.

Since the economy considered features accumulation of (physical and human) capital and growth, it is convenient to normalize aggregate variables in terms of the total wealth  $X_t$ , for each  $t$

$$k_t \equiv \frac{K_t}{X_t}, \quad h_t \equiv \frac{H_t}{X_t}, \quad b_t \equiv \frac{B_t}{X_t}, \quad g_t \equiv \frac{G_t}{X_{t-1}}.$$

With regard to the public expenditure policy, in what follows we shall assume that it is specified in terms of an exogenous sequence of expenditure levels per unit of total wealth  $\{g_t\}_{t=0}^{\infty}$ . Given our interest in the optimal taxes and debt in the long run, this specification ensures that the ratio of public expenditure  $G_t$  to output  $Y_t$  remains the same over time. Since the growth rate of output is endogenously determined, such a property would not be ensured if we adopted a more standard specification where instead  $\{G_t\}_{t=0}^{\infty}$  is exogenously given. But we want to emphasize that our main finding on the long run tax rate on capital income does not depend on our assumption that  $g_t$  instead of  $G_t$  is exogenous. First, it holds without government purchases. Second, as shown in the Appendix, we do obtain a similar result for the case where  $\{G_t\}_{t=0}^{\infty}$  is exogenously given.

Once restated in terms of the normalized variables  $\{k_t, h_t, b_t, \tilde{r}_{t+1}, \tilde{w}_{t+1}, \rho_{t+1}, \eta_{h,t}, \eta_{c,t}, R_{x,t+1}\}_{t=0}^{\infty}$ , the Ramsey problem can then be formulated as a two-step maximization problem. In the first step, we take as arbitrarily given a sequence  $\{\eta_{c,t}, b_t\}_{t=0}^{\infty}$ , and consider the optimal choice of the remaining variables  $\{\tilde{r}_{t+1}, \tilde{w}_{t+1}, \rho_{t+1}, \eta_{h,t}, R_{x,t+1}, k_t, h_t\}_{t=0}^{\infty}$ . Substituting (24) and

(25) into (18), and dividing both sides by  $X_t$ , the government budget constraint becomes

$$\begin{aligned}
g_{t+1} + (1 - \delta_k + \tilde{r}_{t+1})b_t & \tag{31} \\
& = (1 - \eta_{c,t})R_{x,t+1}b_{t+1} + F [(1 - \eta_{c,t})(1 - \eta_{h,t}) - b_t, (1 - \eta_{c,t})\eta_{h,t}] \\
& \quad - \tilde{r}_{t+1} [(1 - \eta_{c,t})(1 - \eta_{h,t}) - b_t] - \tilde{w}_{t+1}(1 - \eta_{c,t})\eta_{h,t}
\end{aligned}$$

Conditions (9), (10), (22), and (31) imply that, for each  $t$ , the choice of  $(\tilde{r}_{t+1}, \tilde{w}_{t+1}, \eta_{h,t}, R_{x,t+1})$  only affects  $\rho_{t+1}$ , and not  $\rho_s$  for any  $s \neq t + 1$ . Therefore, in the first-step problem,  $v_0$  can be maximized by maximizing  $\rho_{t+1}$  separately for each  $t$ . Note also that among the given sequence  $\{\eta_{c,t}, b_t\}_{t=0}^{\infty}$ ,  $\rho_{t+1}$  is only affected by  $b_t$ ,  $b_{t+1}$ , and  $\eta_{c,t}$ . Hence the first-step problem reduces to the following static maximization problem:

$$\rho^R(b_t, b_{t+1}, \eta_{c,t}; g_{t+1}) \equiv \max_{\{\tilde{r}_{t+1}, \tilde{w}_{t+1}, \eta_{h,t}, R_{x,t+1}\}} \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1}, \eta_{h,t}) \tag{32}$$

subject to (22) and (31).

The second-step problem consists then in the choice of the sequence  $\{\eta_{c,t}, b_t\}_{t=0}^{\infty}$  which maximizes  $v_0$ . This problem can be written recursively as:

$$\max_{\{v_{t+1}, b_{t+1}, \eta_{c,t+1}\}_{t=0}^{\infty}} v_0, \tag{33}$$

subject to (12), (14), and  $\rho_{t+1} = \rho^R(b_t, b_{t+1}, \eta_{c,t}; g_{t+1})$ .

To derive some insights on the properties of the solution of the dynamic Ramsey problem and hence of the optimal taxes and debt, it is useful to consider first the case where only a subset of policy instruments at a time is available.

### 3.1 The case of balanced budget: tax labor and subsidize capital

We study first the welfare effects of taxing capital or labor, by examining the case where there are no government purchases nor public debt, thus the budget is balanced at all times:

$$g_t = b_t = 0, \quad \text{for all } t, \tag{34}$$

with  $b_{i,-1} = 0$  for all  $i$ . Under (34), the Ramsey problem reduces to:

$$\max_{\{\tilde{r}, \tilde{w}, \eta_h\}} \rho(\tilde{r}, \tilde{w}, \eta_h) \quad \text{s.t.} \quad F(1 - \eta_h, \eta_h) - \tilde{r}(1 - \eta_h) - \tilde{w}\eta_h = 0. \tag{35}$$

The solution is time invariant and the economy is always on a balanced growth path, as in the benchmark equilibrium of subsection 2.5. Let us denote the variables at the solution with the superscript  $o$ , i.e.,  $v^o$ ,  $\rho^o$ ,  $R_x^o$ ,  $\eta_c^o$ , etc.

The balanced budget requirement implies that the tax revenue on one factor equals the subsidy on the other factor. We show next that taxing labor and subsidizing (physical) capital is welfare improving.

**Proposition 3.** *Under Assumption 1, at the benchmark equilibrium, social welfare increases if a marginal subsidy on capital (and a corresponding tax on labor) is introduced for all  $t$ .*

More specifically, we show in the proof of the proposition that

$$\left( \frac{\partial \rho}{\partial \tilde{r}} + \frac{\partial \rho}{\partial \tilde{w}} \frac{d\tilde{w}}{d\tilde{r}} \right) \Big|_{\tilde{r}=\hat{F}_k, \tilde{w}=\hat{F}_h, \eta_h=\hat{\eta}_h} > 0$$

and, furthermore, that an increase in  $\tilde{r}$  is equivalent to a decrease in  $\tau_k$ . As shown in (30), social welfare increases when  $\rho$  rises.

Hence, even though taxes are distortionary and there is no need for the government to raise tax revenue, in the incomplete markets environment considered, it is beneficial, for agents' welfare, to tax labor and subsidize physical capital. The intuition for this result is simple. In the benchmark equilibrium (with no taxes) individuals are exposed to the risk in their labor income which they are unable to insure. By taxing risky labor income and using the total revenue of this tax to subsidize the riskless return on capital, that is by setting  $\tilde{r} > \hat{F}_k$  and  $\tilde{w} < \hat{F}_h$ , the government can reduce the individual exposure to idiosyncratic risk. Thus, a welfare improvement can be attained by reducing the return of the risky factor and increasing that of the riskless one.<sup>8</sup>

Note that Proposition 3 only characterizes the properties of optimal taxes in a neighborhood of zero, and does not guarantee that the globally optimal tax rate on physical capital is indeed negative in the environment considered, when government consumption and debt are zero. A sufficient condition for this to hold is that:<sup>9</sup>

**Assumption 2.** *The function  $\rho(\tilde{r}, \tilde{w}, \eta_h)$  is such that problem (35) has a unique local maximum.*

The above result tells us that market incompleteness alone does not justify taxing capital income. However, in what follows we show that, once the government is allowed to issue debt, it becomes beneficial to tax capital income (in the long run).

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<sup>8</sup>A related result has been obtained by Eaton and Rosen (1980) and Barsky, Mankiw and Zeldes (1986). Using a two-period model where the second period labor income is subject to idiosyncratic risk, they consider the effect of a combination of a proportional labor income tax and lump-sum transfers. Such a policy has an insurance effect similar to the one discussed here.

<sup>9</sup>This property is satisfied in all the numerical examples considered in the rest of the paper.

### 3.2 Desirability of government debt

Next, we turn our attention to the welfare effects of issuing government debt, when markets are incomplete. We show that, starting from a zero level of government debt, increasing the amount of government debt is welfare improving as long as government purchases are small enough.

Consider the allocation obtained as the solution to the Ramsey problem under (34), that is, with no government debt nor expenditure, studied in the previous subsection. We will investigate whether allowing for an arbitrarily small (positive or negative) level of debt at only one date yields a welfare improvement. This amounts to studying the solutions of the Ramsey problem under the following alternative restriction to (34):

$$b_{T+1} = \bar{b}_{T+1}, \quad b_t = 0, \quad \text{for all } t \neq T + 1, \quad g_t = 0, \quad \text{for all } t,$$

for some given  $\bar{b}_{T+1}$ , with  $b_{i,-1} = 0$  for all  $i$ . The next proposition establishes that having a positive amount of debt,  $\bar{b}_{T+1} > 0$ , is welfare improving.

**Proposition 4.** *Suppose that Assumptions 1 and 2 hold and consider the Ramsey equilibrium with no public debt nor expenditure, that is, under (34). Then increasing  $\bar{b}_{T+1}$  above zero for a given period  $T + 1$  improves the lifetime utility of all individuals.*

To gain some intuition for the result note that, in the light of (30), whether or not increasing  $\bar{b}_{T+1}$  above zero is welfare improving depends on how this change affects the equilibrium values of  $\{\rho_{t+1}\}_{t=0}^{\infty}$ . We show in the proof that only  $\rho_{T+1}$  and  $\rho_{T+2}$  are affected by the change in  $\bar{b}_{T+1}$ . First note that increasing  $\bar{b}_{T+1}$  above zero reduces taxes in period  $T + 1$  and this increases  $\rho_{T+1}$ . The benefit is proportional to the after-tax average rate of return of individual portfolios,  $R_x^o$ , at the Ramsey equilibrium with  $b_t = g_t = 0$  for all  $t$ . This is natural because  $R_x^o$  is the average rate that individuals earn using the proceeds from the tax cut in  $T + 1$ . In contrast, the increase in  $\bar{b}_{T+1}$  has to be offset by a tax increase in period  $T + 2$  to redeem the debt. As a result,  $\rho_{T+2}$  decreases. The cost is proportional to the (before-tax) rate of return on government debt,  $1 - \delta_k + F_k^o$ . Whether or not increasing  $\bar{b}_{T+1}$  is beneficial depends on the comparison between these two terms and we show in the proof that the benefit of increasing  $\bar{b}_{T+1}$  dominates its cost if and only if

$$R_x^o > 1 - \delta_k + F_k^o. \tag{36}$$

As shown in subsection 3.1, under Assumptions 1 and 2 the optimal tax rates when  $b_t = g_t = 0$  for all  $t$  are negative on capital and positive on labor, and this, together with the risky nature of labor income imply that (36) holds, and so that increasing the amount of government debt in one period is welfare improving. The argument can then be extended by continuity to the case where government purchases,  $g_t$ , are sufficiently small.

### 3.3 Ramsey steady state

Finally, we consider the case where the government can freely choose a fiscal policy  $\{\tilde{r}_{t+1}, \tilde{w}_{t+1}, B_t\}_{t=0}^{\infty}$  satisfying (18) and (19). We focus in particular on the properties of the Ramsey equilibrium at a steady state (balanced growth path),<sup>10</sup> and assume so that  $g_t = g \geq 0$  for all  $t$ .

**Proposition 5.** *In the steady state of the Ramsey equilibrium the following condition holds:*

$$R_x = (1 - \delta_k + F_k) \left[ 1 - (1 - \psi)\beta^\psi \rho^{\psi-2} \rho_{\eta_c} \eta_c \right]^{-1} \quad (37)$$

with  $\rho_{\eta_c} \equiv \frac{\partial \rho^R}{\partial \eta_c}$ .

In the proof, we show, by an analogous argument to the one in the previous subsection, that the beneficial effect on  $\rho_t$  and hence also on  $v_t$  of an increase in  $b_t$  is proportional to  $R_x$ , while its cost, due to a reduction of  $\rho_{t+1}$ , is proportional to  $(1 - \delta_k + F_k)$ . There is now an extra term,  $(1 - \beta^\psi \tilde{\rho}^{\psi-2} (1 - \psi) \rho_{\eta_c} \eta_c)^{-1}$ , multiplying the latter, which captures the effect on  $\rho$  of the change in the saving rate,  $1 - \eta_c$ . This term arises when  $b$  takes a nonzero value.

Condition (37) says that, at a steady state, the (before tax) return on government debt and physical capital,  $1 - \delta_k + F_k$ , must equal the average rate of return of private consumers' portfolios,  $R_x$ , after adjusting for the effect of public debt on the consumers' saving rate. It implies that the steady state tax rate on capital income is strictly positive as long as the effect on the saving rate is not too large.<sup>11</sup>

To see this, consider the case where the elasticity of intertemporal substitution  $\psi = 1$ , in which case  $\eta_{c,t}$  is a constant, equal to  $1 - \beta$ , so that the effect on the saving rate is zero. Therefore (37) reduces to  $R_x = 1 - \delta_k + F_k$ . Since human capital is risky but physical capital is not, by the risk aversion of consumers we have  $R_x > 1 - \delta_k + \tilde{r}$  and so  $\tilde{r} < F_k$ , that is  $\tau_k > 0$ . By continuity, the same property holds for  $\psi$  sufficiently close to unity. These findings are summarized in the following result.

**Corollary 6.** *When  $\psi = 1$ , in the steady state of the Ramsey equilibrium we have:*

$$R_x = 1 - \delta_k + F_k \quad (38)$$

and the optimal tax rate on physical capital is positive:

$$\tilde{r} < F_k$$

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<sup>10</sup>Along a balanced growth path, prices and normalized variables  $\{\tilde{r}_t, \tilde{w}_t, b_t, \rho_{t+1}, \eta_{h,t}, \eta_{c,t}, R_{x,t+1}, k_t, h_t\}$  are all constant. Note also that we use the terms “steady state” and “balanced growth path” interchangeably given the fact that a steady state for the normalized variables corresponds to a balanced growth path of the economy. In all the numerical results reported later the solution to the Ramsey problem converges to a steady state.

<sup>11</sup>The steady-state optimal capital tax rate is indeed strictly positive in all the numerical examples considered here.

### 3.4 Discussion

The analysis in this section has identified two roles that taxes and government debt can serve in an economy with incomplete markets. The first one is provision of insurance, that is, it is beneficial to tax a factor that is subject to uninsurable idiosyncratic risks. In our model, labor income is exposed to such risks, which justifies labor income taxes as is demonstrated in Proposition 3. This type of benefits exists regardless of whether individual labor productivity is given exogenously or determined endogenously through human capital accumulation.<sup>12</sup>

The second role is the intertemporal allocation of taxes. This corresponds to the benefits of government debt and capital income taxes described in Propositions 4-6. In the presence of uninsurable risks to human capital accumulation, human capital must yield a higher expected rate of return than physical capital. Hence without taxes on capital income the rate of return faced by the private sector ( $R_x$ ) is necessarily greater than the rate of return faced by the government ( $1 - \delta_k + F_k$ ). As long as this is the case, it is cheaper to borrow for the government than for consumers and increasing government debt is beneficial. Our findings show that when public debt is at the optimal level the tax rate on capital should be increased until the after tax return on consumers' savings equal the before tax return on public debt (possibly with a correction to take into account the effect of debt on the saving rate). This condition can be interpreted as a kind of “no arbitrage condition” between the government and the private sector.

How robustly do this type of benefits exist? Since the benefits of government debt and capital income taxes we have found arise from the rate of return differential between human and physical capital, they would survive in more general models as long as human capital accumulation is riskier than physical capital. And empirical evidence suggests that human capital does have a higher average rate of return than physical capital (e.g., Card (2001), and Palacios-Huerta, (2003)).

The presence of uninsurable risk clearly plays a key role for these results. If agents were able to trade in complete markets so as to fully hedge all risk, so that human capital would also be, effectively, a safe asset we would have  $R_k = R_h = R_x$ , in which case the condition  $R_x = 1 - \delta_k + F_k$  implies that  $\tau_k = 0$ .<sup>13</sup> We should point out however that in our environment market incompleteness alone does not justify capital income taxation, this only happens when the government is allowed to issue debt. As we said in the Introduction, the reasons for this result are quite different from those of the finding of Aiyagari (1995) on the optimality of capital taxation.

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<sup>12</sup>See Gottardi, Kajii, and Nakajima (2013) for the case where individual labor productivity is given exogenously.

<sup>13</sup>This is indeed the case considered by Judd (1985), Chamley (1986), Jones, Manuelli and Rossi (1997).

## 4 Quantitative analysis

In this section we calibrate our model based on some empirical evidence on the U.S. economy, and examine how market incompleteness affects the structure of optimal taxes and debt.

### 4.1 Baseline calibration

Suppose that  $\theta_{i,t} \in \{1+\bar{\theta}, 1-\bar{\theta}\}$ , each occurring with equal probability. The values for the parameters of our model economy,  $\{\beta, \psi, \gamma, A, \alpha, \delta_k, \delta_h, g, \tau_k, \tau_h, \bar{\theta}\}$ , are set as follows. First, the intertemporal elasticity of substitution  $\psi$  is set equal to one and the coefficient of relative risk aversion  $\gamma$  equal to three. Second, the capital share of income  $\alpha$  is set to 0.36, and both the depreciation rates of physical and human capital are  $\delta_k = \delta_h = 0.06$ . Third, the tax rates on capital and labor income are identical,  $\tau_k = \tau_h = \tau$ . Then the benchmark value of the remaining parameters,  $\{\beta, A, g, \tau, \bar{\theta}\}$ , are determined so that the following features of the U.S. economy are replicated: (i) government purchases are 18 percent of GDP; (ii) government debt is 51 percent of GDP; (iii) the capital-output ratio is 2.7; (iv) the growth rate of GDP is 1.6 percent; (v) the variance of the permanent shock to individual labor earnings is 0.0313. The first four facts are based on Chari, Christiano and Kehoe (1994), and the last one on Meghir and Pistaferri (2004).<sup>14</sup> The baseline parameter values are summarized in Table 1.

Column (1) of Table 2 presents the tax rates, the ratio of government debt to GDP, the growth rate, and the (before-tax) premium of the return on human capital that prevail in the balanced-growth path associated with the benchmark parameter values in Table 1. The capital and labor tax rates are identical by construction and equal to 19.95 percent.<sup>15</sup> The debt-GDP ratio, the share of government purchases and the growth rate of the economy are pinned down by our calibration assumptions. The rate of return differential between human and physical capital plays an important role in our set-up to assess the benefits of government debt and capital income taxes and is then an important variable to evaluate the empirical relevance of our model. As reported in the table, the human capital premium in the baseline calibration is 5.28 percent. This is indeed consistent with the evidence given, for instance, by Card (2001) and Palacios-Huerta (2003).

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<sup>14</sup>It is also consistent with the evidence reported by Storesletten, Telmer and Yaron (2004).

<sup>15</sup>Our baseline tax rates (19.95 percent) may be smaller than the values typically used in the literature. For instance, Trostel (1993) uses 40 percent as the benchmark tax rate. The reason for this difference lies in the fact that our model abstracts from transfer payments of the government. As far as the nature of the Ramsey steady state is concerned, this difference is not important, because the Ramsey steady state would not be affected by changing the baseline tax rates, and also because, as discussed in Section 4.4.1, this steady remains unchanged if lump sum transfers independent of the idiosyncratic risks are introduced.

## 4.2 Results

For the economy described in Table 1 we derive the optimal tax and debt policy, obtained as the solution of the Ramsey problem of maximizing consumers' intertemporal welfare, not just their steady state welfare. The tractable nature of the model considered allows us in fact to study also the transitional dynamics of the Ramsey equilibrium, with tax rates which may vary over time. The levels of the tax rates, government debt and the growth rate of income at the Ramsey steady state of the economy are reported in the second column of Table 2. In addition, the third and fourth columns report the corresponding values at the Ramsey steady state without government purchases, respectively, when the level of public debt is optimally chosen and when it is constrained to be zero.

Comparing columns (1) and (2), we see that when taxes and debt are optimally set to maximize consumers' welfare, both the tax rate on labor income and the level of debt-to-GDP are lower than in the case of the baseline policy calibrated on the U.S. economy, while the tax rate on capital income is essentially the same. The last two columns allow then to gain some understanding on the properties of optimal taxes and debt, in light of the results of the previous section.

The case where there are no government purchases ( $g = 0$ ) is in fact a useful benchmark because, if asset markets were complete, in such case the optimal tax rates (and public debt) would all be zero. Therefore, if we find that non-zero tax rates are desirable when  $g = 0$ , this is entirely due to the distortions caused by market incompleteness. In Proposition 3 we have seen that taxing labor income and subsidizing capital income is beneficial because it reduces the risk faced by individuals. Column (4) in Table 2 illustrates the quantitative significance of this finding: when the government is not allowed to borrow or lend ( $b = 0$ ), the optimal tax rate on labor income is 0.19 percent, and the one on capital income is -0.34 percent. The signs are consistent with the proposition recalled above, but the levels are negligible. In contrast, these levels are significantly larger if the government can issue debt, as column (3) shows. In this case, the steady-state debt-to-GDP ratio is positive, in accord with Proposition 4, and quite large (202.6 percent), while the optimal tax rates on labor income and capital income at the steady state are 4.99 percent and 11.56 percent, respectively. Comparing columns (3) and (4), we see that the ability of the government to borrow and lend significantly affects the structure of optimal taxes. Hence assuming an exogenous amount of government debt, which is often done in the existing literature on optimal taxation with incomplete markets, may provide misleading results.

Finally, comparing columns (2) and (3) in Table 2 we see that the introduction of government purchases increases the optimal level of both tax rates, to  $\tau_k = 19.64$  percent and  $\tau_h = 14.88$  percent, and reduces the debt-to-GDP ratio to 0.19 percent. Note that, when the level of public debt is optimally chosen, both in columns (2) and (3) the tax rate on capital is positive, as predicted

by Corollary 6.

How sizeable are the benefits associated with the move from the baseline fiscal policy to the Ramsey policy? This benefits can be measured by the rate of permanent increase in consumption of each individual that makes him/her indifferent between the two policies. As can be seen from Lemma 1, this rate is the same for all consumers and is given by the ratio of the values of  $v_0$  under the two policies in comparison. Table 3 shows the result. When we only compare the steady states associated with the baseline policy and the Ramsey policy, the welfare gain of adopting the Ramsey policy amounts to an increase of about 8.7 percent in each individual's consumption (in accord with the increase in the growth rate of income reported in Table 2). But this number ignores the cost of transition, where a significant increase in taxes takes place to reduce the debt level. When the transition is taken into account, the gain becomes substantially smaller, 0.85 percent, nevertheless a significant amount.

### 4.3 Sensitivity analysis

In this subsection we examine how the debt-to-output ratio and the tax rates at the Ramsey steady state vary for different values of the risk aversion coefficient  $\gamma$ , the intertemporal elasticity of substitution  $\psi$ , and the magnitude of the idiosyncratic risk  $\bar{\theta}$ . For the purpose of normalization, when the values of these parameters are changed we adjust the value of the discount factor  $\beta$  so that the steady-state growth rate under the baseline policy remains equal to 1.6 percent.

Figure 1 plots the results for the changes in risk aversion. We see that the optimal debt-to-output ratio is very sensitive to the choice of the degree of risk aversion. It is about  $-100$  percent when  $\gamma = 1$ , and about 200 percent when  $\gamma = 9$ . Regarding the tax rates, the risk aversion coefficient affects the capital tax rate  $\tau_k$  much more than the labor tax rate  $\tau_h$ .

Figure 2 then shows that the debt-to-output ratio varies significantly also with the magnitude of the idiosyncratic risk. It is negative and large ( $-200$  percent) when there is no idiosyncratic risk ( $\text{std}(\theta) = 0$ ), in accord with the findings mentioned above of the complete market literature. The debt ratio gets larger when risk increases, reaching a zero level when  $\text{std}(\theta)$  is near its baseline level, 0.1585, and a positive level of about 60 percent when  $\text{std}(\theta) = 0.2$ . The two tax rates are very close to each other when the amount of idiosyncratic risk is moderate ( $\text{std}(\theta) < 0.1$ ), but when  $\text{std}(\theta) > 0.1$  the labor tax rate  $\tau_h$  is much less sensitive to changes in the amount of idiosyncratic risk. Most of the increase in the steady state level of debt is then financed with an increase in  $\tau_k$ .

In contrast, we see in Figure 3 that the value of the intertemporal elasticity of substitution does not affect much the optimal debt-ratio and tax levels. This suggests that the saving effect appearing in (37) is quantitatively small.

## 4.4 Non Linear tax policies

So far we have restricted our attention to tax policies consisting in proportional taxes on labor and capital income. In this subsection we extend the analysis to allow for other forms of taxation.

### 4.4.1 Lump sum taxes

We examine first the case where the government can also impose lump sum taxes  $\{T_{i,t} : i \in [0, 1]\}_{t=0}^{\infty}$ , which may depend on the time period  $t$  and the identity  $i$  of an individual, but not on the realization of idiosyncratic shocks  $\{\theta_{i,s}\}_{s=0}^t$ . A fiscal policy is then given now by  $\{\tilde{r}_t, \tilde{w}_t, \{T_{i,t} : i \in [0, 1]\}, B_t\}_{t=0}^{\infty}$ .

Let  $TP_{i,t}$  denote the present-discounted value of the lump sum taxes that individual  $i$  has to pay after period  $t$ :

$$TP_{i,t} \equiv \sum_{j=0}^{\infty} \prod_{s=0}^j (1 - \delta_k + \tilde{r}_{t+1+s})^{-1} T_{i,t+1+j},$$

Notice that for this policy to be feasible, it must be

$$R_{k,0}(k_{i,-1} + b_{i,-1} - TP_{i,-1}) + R_{h,0}\theta_{i,0}h_{i,-1} > 0, \quad \text{for all } i \in [0, 1], \quad (39)$$

to ensure the non negativity of the value of the initial endowment (and hence that the natural debt limit is satisfied).

It is immediate to verify that a competitive equilibrium associated with such policy is also an equilibrium without lump sum taxes where (i) the fiscal policy is given by  $\{\tilde{r}_t, \tilde{w}_t, \hat{B}_t\}_{t=0}^{\infty}$ , with  $\hat{B}_t = B_t - \int_0^1 TP_{i,t} di$ ; and (ii) the consumers' initial endowment of bonds is:

$$\hat{b}_{i,-1} = b_{i,-1} - TP_{i,-1}.$$

Thus the only effect of lump sum taxes is to change the initial distribution of income among consumers. Since the Ramsey steady state does not depend on the initial distribution of income among consumers, the long-run equilibrium is identical with and without lump sum taxes. Therefore, our previous results on the Ramsey steady state remain valid.

### 4.4.2 Nonlinear taxes

Next we investigate the effects of allowing for nonlinear taxes on labor income so that, for instance, we may have progressive income taxation. Although a complete analysis of the optimal fiscal policy in this case is beyond the scope of this paper, we can learn something about these effects by considering the simpler case where nonlinear taxes are only allowed in a single period, say  $t = 1$ . For all the other periods, taxes are restricted to be linear and described as before by  $(\tilde{r}_t, \tilde{w}_t)$ ,  $t \neq 1$ .

Regarding the possible forms of these taxes, we follow Conesa, Kitao and Krueger (2009) in assuming that labor income is taxed according to the following formula:

$$T(\omega_{i,1}) = \tau_{ha} [\omega_{i,1} - (\omega_{i,1}^{-\tau_{hb}} + \tau_{hc})^{-\frac{1}{\tau_{hb}}}], \quad (40)$$

where  $\omega_{i,1} = w_1 \theta_{i,1} h_{i,0}$  is the before-tax labor income of individual  $i$  in period 1,  $T(\omega_{i,1})$  is the labor income tax that he/she must pay, and  $(\tau_{ha}, \tau_{hb}, \tau_{hc})$  are the parameters describing the tax schedule. Thus a fiscal policy is now described by  $\{(\tau_{ha}, \tau_{hb}, \tau_{hc}), \tilde{r}_1, B_1, \{\tilde{r}_t, \tilde{w}_t, B_t\}_{t=2}^\infty\}$ .

Suppose the economy is at the Ramsey steady state with linear taxes at the beginning of period 0. The optimal<sup>16</sup> policy for period 1,  $\{\tau_{ha}, \tau_{hb}, \tau_{hc}, \tilde{r}_1, B_1\}$ , is computed using a grid search algorithm, while the optimal tax rates after period 2,  $\{\tilde{r}_t, \tilde{w}_t, B_t\}_{t=2}^\infty$ , are derived just as before. Let a bar ( $\bar{\cdot}$ ) over a variable indicate then the value in the Ramsey steady state with linear taxes, and a variable with an asterisk ( $\ast$ ) denote its value in the equilibrium where optimal nonlinear labor income taxes are introduced in period  $t = 1$ .

Consider the case where  $g = 0$ , the initial wealth  $x_{0,i}$  is 1.5 for  $i > 0.5$  and 0.5 for  $i \leq 0.5$ , and the rest of the parameter values are as in Table 1. As shown in column (3) in Table 2, the Ramsey steady state with linear taxes has  $\bar{\tau}_k = 0.1156$ ,  $\bar{\tau}_h = 0.0499$ , and  $\bar{b} = 0.2364$ .<sup>17</sup> With nonlinear taxes in period 1, the optimal tax policy at  $t = 1$  is instead given by  $(\tau_{k,1}^\ast, \tau_{ha}^\ast, \tau_{hb}^\ast, \tau_{hc}^\ast) = (0.1256, 0.0599, 0.15, 0.7659)$ , and  $b_1^\ast = 0.2355$ . With the nonlinear function  $T(\omega)$ , both the marginal and the average labor income tax rates can vary across individuals, which may enhance risk sharing among them. It turns out, however, that the optimal variation of the marginal and average tax rates across individuals is very small. The lowest and highest values of the marginal tax rate on labor income in period 1,  $T'(w_1 \theta_{i,1} h_{i,0})$ , are 5.65 percent and 5.79 percent, respectively. The average value of the marginal tax rate is about 5.7 percent, that is greater than  $\bar{\tau}_h$ . Similarly, the lowest and highest value of the average labor income tax rate,  $T(w_1 \theta_{i,1} h_{i,0}) / (w_1 \theta_{i,1} h_{i,0})$ , are 5.5 percent and 5.68 percent, respectively. Its average across individuals is 5.6 percent. The capital income tax rate,  $\tau_{k,1}^\ast$ , is also greater than  $\bar{\tau}_k$ . The normalized level of debt issued in period 1,  $b_1^\ast$ , is lower than  $\bar{b}$ , implying that the amount of taxes collected is larger when non-linear taxes are available. We also evaluate the welfare gain of using nonlinear taxes in period 1, measured in date 0 consumption equivalent:<sup>18</sup> the welfare gain is tiny, less than 0.0002 percent of date-0 consumption.

<sup>16</sup>Since non linear taxes may affect the distribution of income among consumers, the specification of the Pareto weights may now matter. In what follows we restrict attention to the case where these weights are identical across individuals:  $\lambda_i = 1$  for all  $i$ .

<sup>17</sup>Note that  $\bar{b}$  is the steady-state value of  $b_t = B_t / X_t$  (Table 2 reports the steady-state value of  $B_{t-1} / Y_t$  instead).

<sup>18</sup>It is conventional to measure a gain/loss of a policy reform by a proportional increase/decrease of consumption for all periods. But here, since non-linear taxes are introduced only in one period, we measure its gain by a proportional

To assess the robustness of the previous finding, we consider various other specifications of the initial wealth distribution  $x_{0,i}$ ,  $i \in [0, 1]$ . But the basic feature remains identical: introducing nonlinear taxes results in (i) small variation in both the marginal and average labor income tax rates across individuals; (ii) higher average marginal tax rate on labor income; (iii) higher level of the optimal capital income tax rate in period 1; (iv) small welfare gains. Hence introducing nonlinear taxes does not modify the main qualitative findings of the previous sections, and in particular may even strengthen the benefit of capital income taxation with uninsurable shocks to human capital accumulation.

Our result that allowing for nonlinear labor income taxes increases the optimal capital income tax rate in period 1,  $\tau_{k,1}^* > \bar{\tau}_k$ , may appear surprising. To understand this, recall that, as reported above, the optimal (average and marginal) tax on labor is higher. The fact that capital income should be taxed more can then be viewed as a way to ensure that the desired ratio between physical and human capital is attained<sup>19</sup>, as well as the optimal intertemporal allocation of taxes and hence the optimal debt level.

## 5 Conclusion

We have studied the Ramsey taxation problem in an incomplete-market model with risky human capital accumulation. We have analytically demonstrated the benefits of labor and capital income taxation and government debt in such an environment. The benefit of labor income taxes emerges for the standard reason: since labor income is subject to uninsurable idiosyncratic risks, taxing it reduces the risks that workers are exposed to. The main contribution of this paper is the finding of the benefits of government debt and capital income taxation. They arise because of the rate-of-return differential between human and physical capital, which is, in turn, generated by the difference in risk between them. Our quantitative result illustrates that the optimal long-run capital-income tax rate is sizable.

In order to keep the model as transparent and tractable as possible, we have made a number of simplifying assumptions. In the environment considered, even though individuals are heterogeneous, they unanimously agree on the fiscal policy that should be implemented. As a result, the optimal policy is determined independently of the wealth distribution and equilibrium aggregate variables are also independent of the distribution. Furthermore, we have considered nonlinear taxes, but

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increase in just one period (period 0).

<sup>19</sup>Note that allowing the government to have more policy instruments does not necessarily make all equilibrium variables closer to the first-best values. In a related context, this point is emphasized in Dávila, Hong, Krusell, and Rios-Rull (2012).

only in a limited way, and we have not considered aggregate shocks. Extending the model in these directions is left for our future research.

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**Table 1: Baseline parameter values**

parameter	value	description
$\psi$	1	intertemporal elasticity of substitution
$\gamma$	3	risk aversion coefficient
$A$	0.315	coefficient in the production function
$\alpha$	0.36	share of capital
$\delta_k$	0.06	depreciation rate of physical capital
$\delta_h$	0.06	depreciation rate of human capital
$\beta$	0.9511	discount factor
$g$	0.0256	government purchases as a fraction of total wealth
$\tau$	0.1955	tax rate in the baseline policy ( $\tau_{k,t} = \tau_{h,t} = \tau$ )
$\bar{\theta}$	0.1585	idiosyncratic shock

**Table 2: Steady states**

	notation	(1) baseline	(2) Ramsey	(3) $g = 0$	(4) $b = g = 0$
capital tax rate (%)	$\tau_k$	19.95	19.64	11.56	-0.34
labor tax rate (%)	$\tau_h$	19.95	14.88	4.99	0.19
debt-GDP ratio (%)	$\frac{B_{t-1}}{Y_t}$	51	0.19	202.6	0
share of govt purchases (%)	$\frac{G_t}{Y_t}$	18	16.6	0	0
growth rate (%)	$\frac{Y_{t+1}}{Y_t} - 1$	1.6	2.26	3.25	4.81
human capital premium (%)	$(F_h - \delta_h) - (F_k - \delta_k)$	5.28	4.74	2.95	4.86

**Table 3: Welfare gain of adopting the Ramsey policy**

ignoring transition	considering transition
8.7320	0.8494

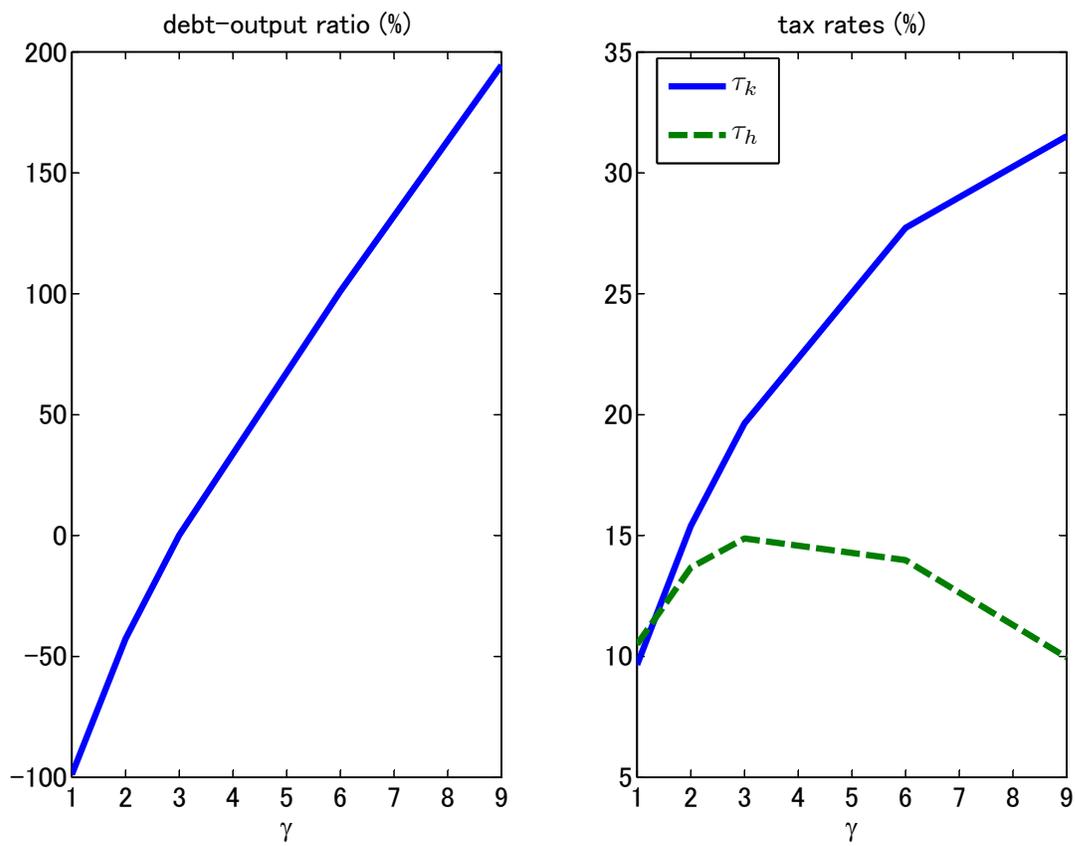


Figure 1: Different values of risk aversion.

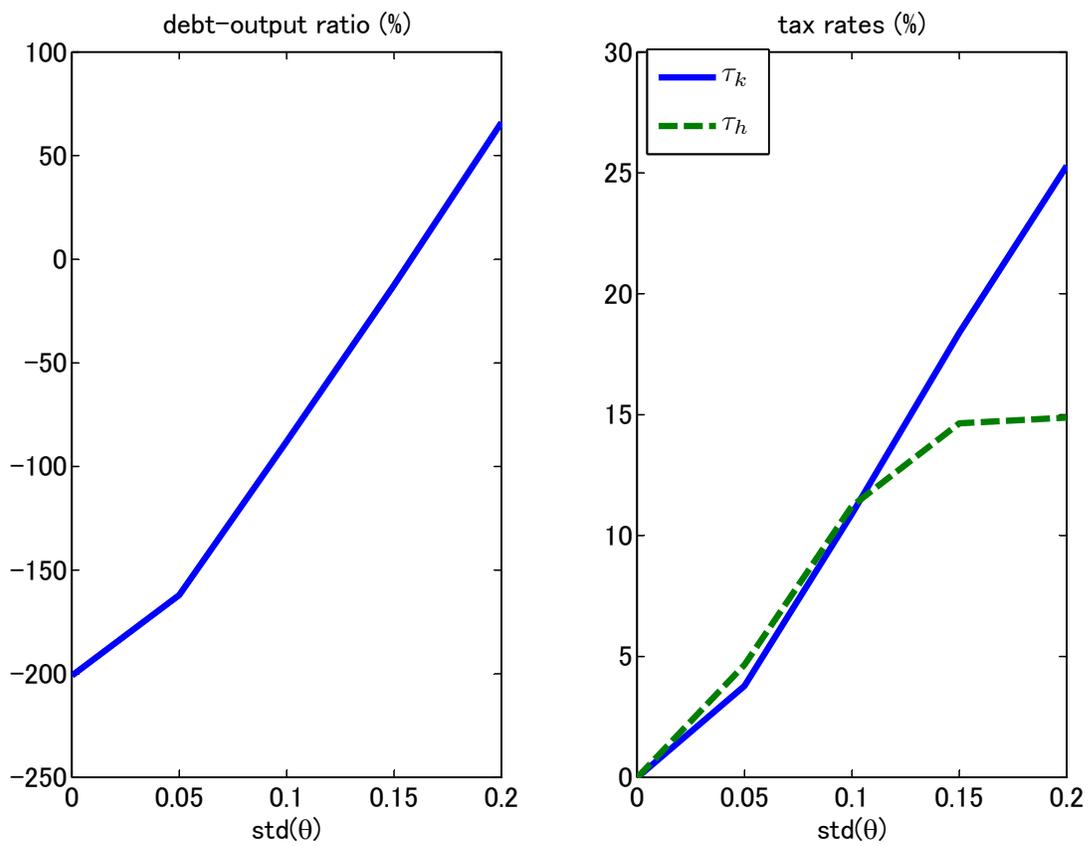


Figure 2: Different values of the idiosyncratic risk.

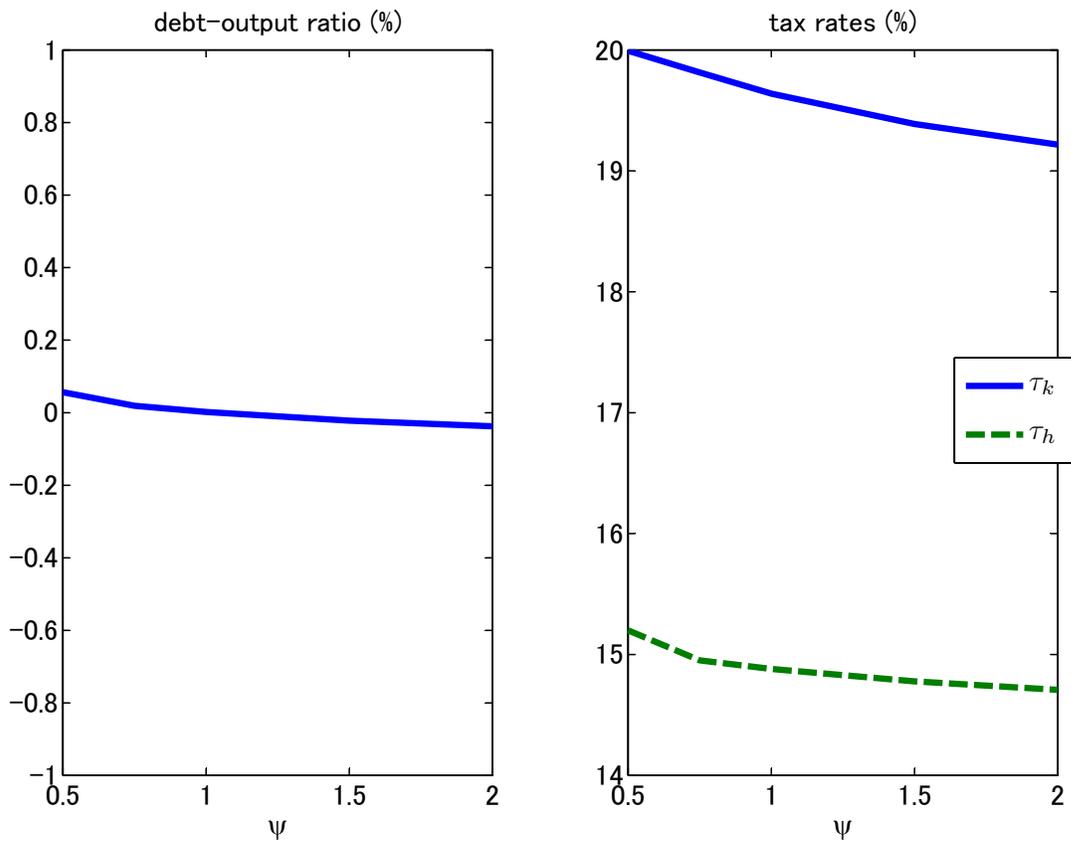


Figure 3: Different values of the intertemporal elasticity of substitution.

# Appendix (to be published online only)

## 1 Proofs

### 1.1 Proof of Lemma 1

The proof of this lemma uses an argument similar to Esptein and Zin (1991) and Angeletos (2007). Since the idiosyncratic shocks,  $\theta_{i,t}$ , are i.i.d. across individuals and across periods, the utility maximization problem of each individual can be expressed as:

$$V_t(x) = \max_{c, \eta_h} \left\{ (1 - \beta)c^{1-\frac{1}{\psi}} + \beta (E_t[V_{t+1}(x')^{1-\gamma}])^{\frac{1-\frac{1}{\psi}}{1-\gamma}} \right\}^{\frac{1}{1-\frac{1}{\psi}}}$$

$$\text{s.t.} \quad x' = (x - c) [R_{k,t+1}(1 - \eta_h) + R_{h,t+1}\theta' \eta_h] \geq 0,$$

$$c \in [0, x], \quad \eta_h \in [0, 1].$$

Here,  $V_t(x)$  is the value function for the utility maximization problem of an individual whose total wealth is  $x$  at the beginning of period  $t$ . We conjecture that there exists a (deterministic) sequence  $\{v_t\}_{t=0}^{\infty}$ , with  $v_t \in \mathbb{R}_+$  for all  $t$ , such that

$$V_t(x) = v_t x$$

Using this conjecture and the budget constraint, we obtain

$$(E_t[V_{t+1}(x')^{1-\gamma}])^{\frac{1}{1-\gamma}} = v_{t+1}(x - c) \left\{ E_t \left[ (R_{k,t+1}(1 - \eta_h) + R_{h,t+1}\theta' \eta_h)^{1-\gamma} \right] \right\}^{\frac{1}{1-\gamma}}$$

It follows that in the above maximization problem the individual chooses the portfolio  $\eta_h$  so as to solve the following maximization problem:

$$\eta_h = \arg \max_{\eta'_h \in [0,1]} \left\{ E_t \left[ (R_{k,t+1}(1 - \eta'_h) + R_{h,t+1}\theta' \eta'_h)^{1-\gamma} \right] \right\}^{\frac{1}{1-\gamma}}$$

Let  $\rho_{t+1}$  denote the maximized value in this problem. Note that neither  $\eta_h$  nor  $\rho_{t+1}$  depends on the initial state  $x$ . That is, under the conjectured value function, all individuals would choose the same portfolio and the same certainty-equivalent rate of return.

Given the certainty-equivalent rate of return,  $\rho_{t+1}$ , the level of consumption is chosen so as to solve

$$\max_{c \in [0, x]} \left\{ (1 - \beta)c^{1-\frac{1}{\psi}} + \beta [v_{t+1}\rho_{t+1}(x - c)]^{1-\frac{1}{\psi}} \right\}^{\frac{1}{1-\frac{1}{\psi}}}$$

The first-order condition for this problem is

$$(1 - \beta)c^{-\frac{1}{\psi}} = \beta v_{t+1}^{1-\frac{1}{\psi}} \rho_{t+1}^{1-\frac{1}{\psi}} (x - c)^{-\frac{1}{\psi}}$$

which leads to

$$\eta_c = \left\{ 1 + \left( \frac{\beta}{1 - \beta} \right)^\psi (v_{t+1} \rho_{t+1})^{\psi-1} \right\}^{-1}$$

where  $\eta_c = \frac{c}{x}$ .

On the other hand, the Bellman equation implies

$$v_t^{1-\frac{1}{\psi}} = (1 - \beta)\eta_c^{1-\frac{1}{\psi}} + \beta (v_{t+1} \rho_{t+1})^{1-\frac{1}{\psi}} (1 - \eta_c)^{1-\frac{1}{\psi}}$$

This equation and the above first-order condition for  $c$  imply that

$$v_t^{\psi-1} = (1 - \beta)^\psi + \beta^\psi v_{t+1}^{\psi-1} \rho_{t+1}^{\psi-1}$$

The bounded solution to this difference equation is

$$v_t = (1 - \beta)^{\frac{\psi}{\psi-1}} \left\{ 1 + \sum_{s=0}^{\infty} \prod_{j=0}^s (\beta^\psi \rho_{t+1+j}^{\psi-1}) \right\}^{\frac{1}{\psi-1}}$$

Also, the consumption rate  $\eta_c$  is

$$\eta_{c,t} = (1 - \beta)^\psi v_t^{1-\psi}$$

It is straightforward to verify that, constructed in this way,  $\{V_t(x), \eta_c, \eta_h\}$  indeed characterizes the solution to the utility maximization problem. The rest of the lemma follows immediately.

## 1.2 Proof of Proposition 3

Totally differentiating the constraint of problem (35), we obtain

$$(\tilde{r} - F_k + F_h - \tilde{w}) d\eta_h - (1 - \eta_h) d\tilde{r} - \eta_h d\tilde{w} = 0.$$

Evaluating this expression at the benchmark equilibrium, where  $G_t = B_t = 0$ ,  $\tilde{r}_t = \hat{F}_k$  and  $\tilde{w}_t = \hat{F}_h$ , for all  $t$ , yields

$$(1 - \hat{\eta}_h) d\tilde{r} + \hat{\eta}_h d\tilde{w} = 0.$$

Thus, to satisfy the balanced budget,  $\tilde{r}$  and  $\tilde{w}$  must satisfy the following relationship around  $(\tilde{r}, \tilde{w}) = (\hat{F}_k, \hat{F}_h)$ :

$$\frac{d\tilde{w}}{d\tilde{r}} = -\frac{1 - \hat{\eta}_h}{\hat{\eta}_h}.$$

Hence the effect of a marginal change in  $\tilde{r}$ , taking into account the induced change in  $\tilde{w}$  via the government budget constraint, is given by  $\frac{\partial \rho}{\partial \tilde{r}} - \frac{1-\hat{\eta}_h}{\hat{\eta}_h} \frac{\partial}{\partial \tilde{w}}$  and will be denoted by  $\frac{d\rho}{d\tilde{r}}$ . Since the lifetime utility is increasing in  $\rho_t$  for each  $t$ , it suffices to show that  $\frac{d\rho}{d\tilde{r}} > 0$ .

The envelope theorem implies that  $\frac{\partial \rho}{\partial \eta_h} = 0$  at the benchmark equilibrium. It follows that

$$\begin{aligned} \frac{d\rho}{d\tilde{r}} &= \hat{\rho}^\gamma E \left[ \hat{R}_{x,\theta}^{-\gamma} \left\{ (1 - \hat{\eta}_h) + \theta \hat{\eta}_h \frac{d\tilde{w}}{d\tilde{r}} \right\} \right], \\ &= \hat{\rho}^\gamma E \left[ \hat{R}_x(\theta)^{-\gamma} (1 - \theta) \right] (1 - \hat{\eta}_h), \end{aligned}$$

where  $\hat{R}_x(\theta) \equiv (1 - \delta_k + \hat{F}_k)(1 - \hat{\eta}_h) + (1 - \delta_h + \hat{F}_h)\theta\hat{\eta}_h$ . Since  $E(\theta) = 1$ , we have

$$E \left[ \hat{R}_x(\theta)^{-\gamma} (1 - \theta) \right] = \text{Cov}(\hat{R}_x(\theta)^{-\gamma}, 1 - \theta) > 0,$$

where the inequality follows from the fact that both  $\hat{R}_x(\theta)^{-\gamma}$  and  $1 - \theta$  are decreasing functions of  $\theta$ . Given that  $\hat{\eta}_h < 1$ , this proves that  $\frac{d\rho}{d\tilde{r}} > 0$ .

It remains to show that the after-tax rental rate of capital,  $\tilde{r}$ , and the tax rate on capital income,  $\tau_k$ , move in the opposite directions around the benchmark equilibrium. Since  $\tau_k = 1 - \frac{\tilde{r}}{F_k}$ , we have

$$\frac{d\tau_k}{d\tilde{r}} = \frac{-\hat{F}_k + (-\hat{F}_{kk} + \hat{F}_{kh}) \frac{d\eta_h}{d\tilde{r}}}{\hat{F}_k^2}. \quad (41)$$

Differentiating the individual first order conditions (15) yields

$$\left\{ \Phi_{\tilde{r}} - \frac{1 - \hat{\eta}_h}{\hat{\eta}_h} \Phi_{\tilde{w}} \right\} d\tilde{r} + \Phi_{\eta_h} d\eta_h = 0,$$

so that

$$\frac{d\eta_h}{d\tilde{r}} = \frac{\frac{1-\hat{\eta}_h}{\hat{\eta}_h} \Phi_{\tilde{w}} - \Phi_{\tilde{r}}}{\Phi_{\eta_h}}. \quad (42)$$

Thus we obtain

$$\frac{d\tau_k}{d\tilde{r}} = \frac{1}{\hat{F}_k^2} \frac{-\hat{F}_k \Phi_{\eta_h} + (-\hat{F}_{kk} + \hat{F}_{kh}) \left( \frac{1-\hat{\eta}_h}{\hat{\eta}_h} \Phi_{\tilde{w}} - \Phi_{\tilde{r}} \right)}{\Phi_{\eta_h}} < 0,$$

since by Assumption 1 we have  $\Phi_{\tilde{w}} > 0$ ,  $\Phi_{\tilde{r}} < 0$ , while  $\Phi_{\eta_h} < 0$  follows from the strict concavity of  $\rho(\tilde{r}, \tilde{w}, \eta_h)$  and  $F_{kh} = (1 - \alpha)\alpha k^{\alpha-1} h^{-\alpha} > 0$ . This completes the proof.

### 1.3 Proof of Proposition 4

We are interested in the welfare effect of a marginal variation of  $\bar{b}_{T+1}$  evaluated at  $\bar{b}_{T+1} = 0$ , that is the sign of  $dv_0/d\bar{b}_{T+1}|_{\bar{b}_{T+1}=0}$ . Denote the variables solving the Ramsey problem under (??) as  $v_t(\bar{b}_{T+1})$ ,  $\rho_t(\bar{b}_{T+1})$ , etc.. It is immediate to see that its solution is the same as under (34) for all periods except two,

$$\rho_t(\bar{b}_{T+1}) = \rho^o, \quad \forall t \neq T+1, T+2 \quad (43)$$

Hence from (12) we get  $v_t(\bar{b}_{T+1}) = v^o$ ,  $\forall t \geq T + 2$ , and  $dv_0/dv_T > 0$ , so that

$$\left. \frac{dv_0}{db_{T+1}} \right|_{\bar{b}_{T+1}=0} \geq 0 \quad \Longleftrightarrow \quad \left. \frac{dv_T}{db_{T+1}} \right|_{\bar{b}_{T+1}=0} \geq 0$$

We have so<sup>20</sup>  $\rho_{T+2}(\bar{b}_{T+1}) = \rho^R(\bar{b}_{T+1}, 0, \eta_{c,T+1}(\bar{b}_{T+1}))$ . Recalling again (12), we obtain

$$v_{T+1}(\bar{b}_{T+1}) = \left\{ (1 - \beta)^\psi + \beta^\psi \rho_{T+2}(\bar{b}_{T+1})^{\psi-1} v_{T+2}(\bar{b}_{T+1})^{\psi-1} \right\}^{\frac{1}{\psi-1}}. \quad (44)$$

Here, note that (43) implies  $\partial v_{T+2}/\partial \bar{b}_{T+1} = 0$ . In addition,  $\partial \rho^R(0, 0, \eta_c)/\partial \eta_c = 0$ .<sup>21</sup> Differentiating then  $v_{T+1}(\bar{b}_{T+1})$  with respect to  $\bar{b}_{T+1}$  and evaluating it at  $\bar{b}_{T+1} = 0$  yields

$$\left. \frac{dv_{T+1}}{d\bar{b}_{T+1}} \right|_{\bar{b}_{T+1}=0} = \beta^\psi (\rho^o)^{\psi-2} \rho_1^o v^o, \quad (45)$$

where  $\rho_1^o \equiv \partial \rho^R(b, b', \eta_c^o)/\partial b$  evaluated at  $b = b' = 0$ .<sup>22</sup>

Next, consider the expression analogous to (44) for date  $T$ :

$$v_T(\bar{b}_{T+1}) = \left\{ (1 - \beta)^\psi + \beta^\psi (\rho_{T+1}(\bar{b}_{T+1}))^{\psi-1} v_{T+1}(\bar{b}_{T+1})^{\psi-1} \right\}^{\frac{1}{\psi-1}}. \quad (46)$$

Its derivative with respect to  $\bar{b}_{T+1}$ , evaluated at  $\bar{b}_{T+1} = 0$ , using (45) and again the fact that  $\partial \rho^R/\partial \eta_{c,T}|_{\bar{b}_{T+1}=b_T=0} = 0$ , equals

$$\left. \frac{dv_T}{d\bar{b}_{T+1}} \right|_{\bar{b}_{T+1}=0} = \beta^\psi (\rho^o)^{\psi-2} v^o \left[ \rho_2^o + \beta^\psi (\rho^o)^{\psi-1} \rho_1^o \right],$$

where  $\rho_2^o \equiv \partial \rho^R(b, b', \eta_c^o)/\partial b'$  evaluated at  $b = b' = 0$ .

Let us denote then by  $\lambda(b, b', \eta_c)$  the Lagrange multiplier on the flow budget constraint for the government in problem (32) and by  $\eta_h(b, b', \eta_c)$ ,  $\tilde{r}(b, b', \eta_c)$ ,  $\tilde{w}(b, b', \eta_c)$ , and  $R_x(b, b', \eta_c)$  its solution. Using the envelope property and the fact that  $b, b'$  only appear in this, first constraint (31) of the

<sup>20</sup>Here and in what follows we omit the dependence of  $\rho^R$  on  $g$  whenever  $g_t$  is constant across periods.

<sup>21</sup>To see this, recall from the definition of  $\rho^R(b, b', \eta_c)$  in (32) that  $\eta_c$  affects  $\rho^R$  only through the government budget constraint (31). Consider the associated function:

$$\begin{aligned} f(b, b', \eta_c, \eta_h, \tilde{r}, \tilde{w}, R_x) \\ \equiv g + (1 - \delta_k + \tilde{r})b - (1 - \eta_c)R_x b' - F[(1 - \eta_c)(1 - \eta_h) - b, (1 - \eta_c)\eta_h] \\ + \tilde{r}[(1 - \eta_c)(1 - \eta_h) - b] + \tilde{w}(1 - \eta_c)\eta_h \end{aligned}$$

We have  $\left. \frac{\partial f}{\partial \eta_c} \right|_{b=b'=0} = 0$  and so, by the envelope theorem we get the claimed property.

<sup>22</sup>The superscript  $^o$  indicates, as in the main text, variables evaluated at a solution of the Ramsey problem under the constraint  $b_t = g_t = 0$  for all  $t$ .

problem, we obtain, when  $b_t = g_t = 0$  for all  $t$ :<sup>23</sup>

$$\begin{aligned}\rho_1^o &= -\lambda^o(1 - \delta_k + F_k^o), \\ \rho_2^o &= \lambda^o \beta^\psi (\rho^o)^{\psi-1} R_x^o,\end{aligned}$$

since

$$\eta_c^o = 1 - \beta^\psi (\rho^o)^{\psi-1}.$$

Therefore,

$$\frac{dv_T}{d\bar{b}_{T+1}} = \xi [R_x^o - (1 - \delta_k + F_k^o)], \quad (47)$$

where

$$\xi \equiv \beta^{2\psi} (\rho^o)^{2\psi-3} \lambda^o v^o$$

and  $\xi > 0$  since  $\lambda^o > 0$ , as shown at the end of this proof.

Under Assumptions 1 and 2, as argued in Section 3.1, we have  $\tilde{r}^o > F_k^o$ . Because the investment in human capital is risky, its expected return must be greater than the rate of return on physical capital:

$$1 - \delta_k + \tilde{r}^o < 1 - \delta_h + \tilde{w}^o$$

It follows that

$$\begin{aligned}R_x^o &= [1 - \delta_k + \tilde{r}^o] (1 - \eta_h^o) + [1 - \delta_h + \tilde{w}^o] \eta_h^o \\ &> 1 - \delta_k + \tilde{r}^o > 1 - \delta_k + F_k^o\end{aligned} \quad (48)$$

To establish the sign of (47) and thus completing the proof it remains then to prove that  $\lambda^o > 0$ . As argued in Section 3.1, when  $b_t = g_t = 0$  for all  $t$ , problem (32) reduces to (35), whose first order conditions are:

$$\begin{aligned}\frac{\partial \rho}{\partial \tilde{r}} - (1 - \eta_h^o) \lambda^o &= 0, \\ \frac{\partial \rho}{\partial \tilde{w}} - \eta_h^o \lambda^o &= 0, \\ \frac{\partial \rho}{\partial \eta_h} + \lambda^o (-F_k^o + F_h^o + \tilde{r}^o - \tilde{w}^o) &= 0.\end{aligned}$$

Since  $\partial \rho / \partial \tilde{r} > 0$ , which follows from the definition of  $\rho(\cdot)$  in (8), and  $\eta_h^o \in (0, 1)$ , it follows that  $\lambda^o > 0$ .

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<sup>23</sup>To better understand the form of these expressions, notice that, as we see from (31), a marginal increase of  $\bar{b}_{T+1}$  relaxes this constraint at  $T + 1$  yielding a gain of  $\lambda^o (1 - \eta_c) R_x$ , while tightening this constraint at  $T + 2$  with a loss of  $\lambda^o \beta^\psi (\rho^o)^{\psi-1} (1 - \delta_k + F_k^o)$  (recall that  $\rho_1^o$  is multiplied by  $\beta^\psi (\rho^o)^{\psi-1}$  in the expression of  $dv_T/db_{T+1}$ ). Since  $(1 - \eta_c) = \beta^\psi (\rho^o)^{\psi-1}$ , the comparison of these two reduce to the comparison between  $R_x$  and  $(1 - \delta_k + F_k^o)$ .

## 1.4 Proof of Proposition 5

The Lagrangean for problem (33), using (12) and (14) to substitute for  $\rho_{t+1}$  and  $\eta_{c,t}$ , is

$$v_0 + \sum_{t=0}^{\infty} \lambda_t^v \left\{ (1-\beta)^\psi + \beta^\psi \rho^R(b_t, b_{t+1}, (1-\beta)^\psi v_t^{1-\psi})^{\psi-1} v_{t+1}^{\psi-1} - v_t^{\psi-1} \right\}.$$

The first-order condition with respect to  $b_{t+1}$  is then

$$\lambda_t^v \beta^\psi \rho_{t+1}^{\psi-2} \rho_{2,t+1} v_{t+1}^{\psi-1} + \lambda_{t+1}^v \beta^\psi \rho_{t+2}^{\psi-2} \rho_{1,t+2} v_{t+2}^{\psi-1} = 0, \quad (49)$$

where  $\rho_{t+1} \equiv \rho^R(b_t, b_{t+1}, \eta_{c,t})$ ,  $\rho_{2,t+1} \equiv \partial \rho^R(b_t, b_{t+1}, \eta_{c,t}) / \partial b_{t+1}$ , and  $\rho_{1,t+2} \equiv \partial \rho^R(b_{t+1}, b_{t+2}, \eta_{c,t+1}) / \partial b_{t+1}$ .

The first-order condition for  $v_{t+1}$  is

$$\lambda_t^v \beta^\psi \rho_{t+1}^{\psi-1} v_{t+1}^{\psi-2} + \lambda_{t+1}^v \beta^\psi \rho_{t+2}^{\psi-2} \rho_{\eta_c, t+2} (1-\beta)^\psi (1-\psi) v_{t+1}^{-\psi} v_{t+2}^{\psi-1} - \lambda_{t+1}^v v_{t+1}^{\psi-2} = 0, \quad (50)$$

where  $\rho_{\eta_c, t+2} \equiv \partial \rho^R(b_{t+1}, b_{t+2}, \eta_{c,t+1}) / \partial \eta_{c,t+1}$ .

In a steady-state equilibrium, equation (49) reduces to

$$\rho_2 + \frac{\lambda_{t+1}^v}{\lambda_t^v} \rho_1 = 0 \quad (51)$$

and equation (50) to

$$\frac{\lambda_{t+1}^v}{\lambda_t^v} = \beta^\psi \rho^{\psi-1} \left( 1 - \beta^\psi \rho^{\psi-1} (1-\beta)^\psi (1-\psi) \frac{\rho_{\eta_c} v^{1-\psi}}{\rho} \right)^{-1}, \quad (52)$$

where the term in parenthesis captures the effect on  $\rho$  of the change in the savings rate, given by the second term in (50), which only arises (as we saw in footnote 23) when debt is nonzero.

By a similar argument to the one in the proof of Proposition 4 above, at a steady state equilibrium the derivative of  $\rho^R$  with respect to  $b$  and  $b'$  satisfies

$$\begin{aligned} -\frac{\rho_1^R}{\rho_2^R} &= \frac{1 - \delta_k + F_k}{(1 - \eta_c) R_x} \\ &= \frac{1 - \delta_k + F_k}{\beta^\psi \tilde{\rho}^{\psi-1} R_x}, \end{aligned} \quad (53)$$

where, for the second equality, we used again (14),  $\eta_c = (1-\beta)^\psi v^{1-\psi}$ , and constraint (12),  $v^{\psi-1} = (1-\beta)^\psi + \beta^\psi \tilde{\rho}^{\psi-1} v^{\psi-1}$ , of problem (33).

Combining (51)-(53) and using again (14), yields the claimed result:

$$R_x = (1 - \delta_k + F_k) \left[ 1 - (1-\psi) \beta^\psi \rho^{\psi-2} \rho_{\eta_c} \eta_c \right]^{-1}.$$

## 2 Exogenous government purchases

Here we extend our analysis to the case where the public expenditure policy is specified in terms of an exogenous sequence of absolute levels of expenditure  $\{G_t\}_{t=0}^{\infty}$  (rather than per unit of total wealth). We will obtain conditions characterizing the Ramsey steady state which are analogous to those obtained in Proposition 5 and Corollary 6. Hence, also in the case of exogenous  $G_t$ , the capital income tax rate must be positive in the long run, as long as the effect on the saving rate is small enough.

When the sequence  $\{G_t\}_{t=0}^{\infty}$  is exogenously given, we can no longer use the recursive approach followed in the paper to solve the Ramsey problem in the case where  $\{g_t\}_{t=0}^{\infty}$  is exogenously given. We solve instead the problem in a more direct way. Given  $X_0$  and  $b_0$ , the Ramsey problem consists in the maximization of  $v_0$  with respect to  $\{b_{t+1}, X_{t+1}, v_{t+1}, \tilde{r}_{t+1}, \tilde{w}_{t+1}\}_{t=0}^{\infty}$  subject to

$$\begin{aligned} v_t^{\psi-1} &= (1 - \beta)^\psi + \beta^\psi \rho_{t+1}^{\psi-1} v_{t+1}^{\psi-1} \\ \frac{G_{t+1}}{X_t} + (1 - \delta_k + \tilde{r}_{t+1})b_t &= (1 - \eta_{c,t})R_{x,t+1}b_{t+1} + F(k_t, h_t) - \tilde{r}_{t+1}k_t - \tilde{w}_{t+1}h_t \\ \frac{X_{t+1}}{X_t} &= (1 - \eta_{c,t})R_{x,t+1}, \end{aligned}$$

where  $\eta_{h,t}$ ,  $\eta_{c,t}$ ,  $\rho_{t+1}$ ,  $R_{x,t+1}$ ,  $k_t$ , and  $h_t$  are the following functions of  $\tilde{r}_{t+1}$ ,  $\tilde{w}_{t+1}$ ,  $b_t$ , and  $v_t$ :

$$\begin{aligned} \eta_{h,t} &= \eta_h(\tilde{r}_{t+1}, \tilde{w}_{t+1}) \equiv \arg \max_{\eta_h} \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1}, \eta_h), \\ \rho_{t+1} &= \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1}) \equiv \max_{\eta_h} \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1}, \eta_h), \\ R_{x,t+1} &= R_x(\tilde{r}_{t+1}, \tilde{w}_{t+1}) \equiv (1 - \delta_k + \tilde{r}_{t+1})(1 - \eta_h(\tilde{r}_{t+1}, \tilde{w}_{t+1})) + (1 - \delta_h + \tilde{w}_{t+1})\eta_h(\tilde{r}_{t+1}, \tilde{w}_{t+1}), \\ \eta_{c,t} &= \eta_c(v_t) \equiv (1 - \beta)^\psi (v_t)^{1-\psi}, \\ k_t &= k(\tilde{r}_{t+1}, \tilde{w}_{t+1}, b_t, v_t) \equiv (1 - \eta_c(v_t))(1 - \eta_h(\tilde{r}_{t+1}, \tilde{w}_{t+1})) - b_t, \\ h_t &= h(\tilde{r}_{t+1}, \tilde{w}_{t+1}, v_t) \equiv (1 - \eta_c(v_t))\eta_h(\tilde{r}_{t+1}, \tilde{w}_{t+1}), \end{aligned}$$

The Lagrangean for this problem is then:

$$\begin{aligned} v_0 + \sum_{t=0}^{\infty} &\left[ \lambda_{v,t} \left\{ (1 - \beta)^\psi + \beta^\psi \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1})^{\psi-1} v_{t+1}^{\psi-1} - v_t^{\psi-1} \right\} \right. \\ &+ \lambda_{b,t} \left\{ [1 - \eta_c(v_t)] R_x(\tilde{r}_{t+1}, \tilde{w}_{t+1}) b_{t+1} + F[k(\tilde{r}_{t+1}, \tilde{w}_{t+1}, b_t, v_t), h(\tilde{r}_{t+1}, \tilde{w}_{t+1}, v_t)] \right. \\ &\quad \left. - \tilde{r}_{t+1} k(\tilde{r}_{t+1}, \tilde{w}_{t+1}, b_t, v_t) - \tilde{w}_{t+1} h(\tilde{r}_{t+1}, \tilde{w}_{t+1}, v_t) - \frac{G_{t+1}}{X_t} - (1 - \delta_k + \tilde{r}_{t+1}) b_t \right\} \\ &\left. + \lambda_{x,t} \left\{ [1 - \eta_c(v_t)] R_x(\tilde{r}_{t+1}, \tilde{w}_{t+1}) - \frac{X_{t+1}}{X_t} \right\} \right]. \end{aligned}$$

The first order conditions for  $v_t$ ,  $b_t$ , and  $\tilde{r}_{t+1}$  are so, respectively,<sup>24</sup>

$$0 = -\lambda_{v,t} \frac{v_t^{\psi-2}}{\psi-1} + \lambda_{v,t-1} \frac{\beta^\psi}{\psi-1} \rho_{t+1}^{\psi-1} v_{t+1}^{\psi-2} \quad (54)$$

$$+ \lambda_{b,t} \eta'_c(v_t) \left\{ -R_{x,t+1} b_{t+1} - F_{k,t} (1 - \eta_{h,t}) - F_{h,t} \eta_{h,t} + \tilde{r}_{t+1} (1 - \eta_{h,t}) + \tilde{w}_{t+1} \eta_{h,t} \right\} \\ - \lambda_{x,t} \eta'_c(v_t) R_{x,t+1},$$

$$0 = \lambda_{b,t-1} (1 - \eta_{c,t-1}) R_{x,t} - \lambda_{b,t} (1 - \delta_k + F_{k,t}), \quad (55)$$

$$0 = (\psi - 1) \lambda_{v,t} \beta^\psi \rho_{t+1}^{\psi-2} \rho_{r,t+1} v_{t+1}^{\psi-2} \\ + \lambda_{b,t} \left\{ (1 - \eta_{c,t}) R_{x,r,t+1} b_{t+1} + F_{k,t} k_{r,t} + F_{h,t} h_{r,t} - k_t - \tilde{r}_{t+1} k_{r,t} - \tilde{w}_{t+1} h_{r,t} - b_t \right\} \\ + \lambda_{x,t} (1 - \eta_{c,t}) R_{x,r,t+1}, \quad (56)$$

where  $\eta'_c(v_t) \equiv d\eta_c(v_t)/dv_t$ ,  $F_{k,t} \equiv \partial F(k_t, h_t)/\partial k_t$ ,  $F_{h,t} \equiv \partial F(k_t, h_t)/\partial h_t$ ,  $\rho_{r,t+1} \equiv \partial \rho(\tilde{r}_{t+1}, \tilde{w}_{t+1})/\partial \tilde{r}_{t+1}$ ,  $R_{x,r,t+1} \equiv \partial R_x(\tilde{r}_{t+1}, \tilde{w}_{t+1})/\partial \tilde{r}_{t+1}$ ,  $k_{r,t} \equiv \partial k(\tilde{r}_{t+1}, \tilde{w}_{t+1}, b_t, v_t)/\partial \tilde{r}_{t+1}$ , and  $h_{r,t} \equiv \partial h(\tilde{r}_{t+1}, \tilde{w}_{t+1}, v_t)/\partial \tilde{r}_{t+1}$ .

Assuming that  $G_t$  grows at an exogenous, constant rate  $\gamma_G > 0$ , we focus again our attention on a steady state (balanced growth path) where all the variables in equations (54)-(56) remain constant, except for the Lagrange multipliers,  $\lambda_{v,t}$ ,  $\lambda_{b,t}$ , and  $\lambda_{x,t}$  that grow at the same rate:

$$\frac{\lambda_{v,t}}{\lambda_{v,t-1}} = \frac{\lambda_{b,t}}{\lambda_{b,t-1}} = \frac{\lambda_{x,t}}{\lambda_{x,t-1}} \equiv \gamma_\lambda.$$

Since  $\rho$  is constant we have  $v = (1 - \beta)^\psi / (1 - \beta^\psi \rho^{\psi-1})$ . Also,  $\eta_c = (1 - \beta)^\psi v^{1-\psi}$ , and so

$$\beta^\psi \rho^{\psi-1} = 1 - \eta_c.$$

It then follows from equation (54) that, along a balanced growth path,

$$\frac{\lambda_{v,t}}{\lambda_{v,t-1}} = (1 - \eta_c) + \Lambda \eta'_c(v),$$

where  $\Lambda$  is the term

$$\Lambda \equiv \frac{\psi - 1}{v^{\psi-2}} \left[ \frac{\lambda_{b,t}}{\lambda_{v,t-1}} \left\{ -R_x b - F_k (1 - \eta_h) - F_h \eta_h + \tilde{r} (1 - \eta_h) + \tilde{w} \eta_h \right\} - \frac{\lambda_{x,t}}{\lambda_{v,t-1}} R_x \right],$$

a constant given the fact that all Lagrange multipliers grow at the same rate.

We can then use equation (55) to derive the following steady-state condition which is the counterpart of the one in Proposition 5:

$$R_x = (1 - \delta_k + F_k) \left[ 1 + \frac{\Lambda \eta'_c(v)}{1 - \eta_c} \right]. \quad (57)$$

---

<sup>24</sup>To derive the steady state condition determining the tax rate on capital we do not have to use the first-order conditions with respect to  $\tilde{w}_{t+1}$  or  $X_{t+1}$ . But, of course, we would need those conditions to derive all the steady state equilibrium variables.

Just as in the case of a constant, exogenously given level of  $g$ , this condition implies that at a Ramsey steady state the average rate of return on consumers' portfolios,  $R_x$ , is equal to the before tax return on physical capital (or equivalently the cost of government debt),  $1 - \delta_k + F_k$ , augmented with the effect of public debt on the saving rate,  $\Lambda\eta'_c/(1 - \eta_c)$ . As long as the latter effect is small, we get again  $R_x \approx 1 - \delta_k + F_k$ , which implies that the optimal capital tax rate is positive in the long run:  $\tau_k > 0$ .

When  $\psi = 1$ , again the effect on the saving rate vanishes, so that condition (57) reduces to

$$R_x = 1 - \delta_k + F_k,$$

which is identical to the condition derived in Corollary 6.

### 3 Algorithm to solve the model numerically

The Ramsey equilibrium for our model can be computed in a straightforward way. The function  $\rho^R(b, b', \eta_c)$  is computed as the solution to the maximization problem defined in (32). Then the steady state value of  $b$  is obtained by solving equation (37).

The transitional dynamics is computed for the calibrated economy where  $\psi = 1$ . In this case  $\eta_c$  is constant, so the function above can be written simply as  $\rho^R(b, b')$  and (30) simplifies to

$$\ln(v_0) = \sum_{t=0}^{\infty} \beta^{t+1} \ln(\rho_{t+1}).$$

In the dynamic programming formulation, the Ramsey problem (33) can be written as

$$\ln v(b) = \max_{b'} \beta \ln \rho^R(b, b') + \beta \ln v(b').$$

This problem is solved by discretizing the state space and by the value function iteration.