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Fiscal policy and human capital in the race against the machine*

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Abstract

We analyze the role of fiscal policy and education spending on economic growth and inequality in a dynamic growth model with automation and endogenous human capital. While automation is complementary to high-skilled workers, it substitutes for low-skilled workers leading to an increase in wage inequality. Government affects the economy through taxation, education spending, and redistribution. While redistribution reduces inequality at the cost of lower economic growth, education spending boosts production exacerbating inequality due to the stronger effect of education spending on the human capital of high-skilled workers. The introduction of endogenous human capital, therefore, implies that an increase in taxation, by increasing both transfers and education spending, has an ambiguous effect on inequality. Estimating the optimal tax schedule, we observe that while the labor tax first increases and then reduces over time, the opposite holds for the robot tax. Technological progress in automated technology, indeed, by increasing inequality leads to an optimal adjustment in the fiscal policy mix in favor of the relatively more redistributive robot tax. This result is also robust to the inclusion of private college education spending.

JEL classification: E23, E25, H23, O31, O33, O40

Keywords: Automation, Inequality, R&D, Endogenous Education, Education spending

1 Introduction

Technological advancement is recognized to be a principal driver of economic growth. However, in the last decades, this progress has also contributed to rising inequality due to the skill-biased

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nature of technical change and its interaction with capital accumulation. Automation, that is, the automated operation of production tasks through the use of machines (robots, artificial intelligence, etc.), constitutes a particular form of this process where skills embodied in human labor display different degrees of complementarity to automated technologies: While high-skilled workers tend to benefit from an increase in the productivity (or a reduction in the price) of automated technologies, the opposite holds for low-skilled workers who can actually be substituted by machines. Skill-biased technological progress with these features thus induces a pattern of rising skill premia along with stagnating, or indeed falling, wages for less-educated workers (Autor, 2019).

To mitigate the adverse effects of automation on inequality, the government can then use taxes and transfers that redistribute resources from richer households to poorer ones. These interventions, however, create distortions in the incentives to acquire the skills that are complementary to automated technology and thus disrupt the underlying mechanism of economic growth. Therefore, transfers reduce inequality at the cost of lower economic growth.

Based on this notion of automation and the trade-off between growth and redistribution it entails, we examine the role of fiscal policy within an overlapping generations model where both technology and skills are endogenous. Allowing for endogenous dynamics in R&D-driven productivity and human capital formation is essential to give full account of the ‘*race between education and technology*’ (Goldin and Katz, 2010) which determines the evolution of income as well as its distribution over time. This is because the demand for human capital and skills is shaped by technical progress, whereas their supply is shaped by the education system.

In this setup, wages for individual workers are endogenous because of three key mechanisms. First, workers’ education decisions determine their ultimate type (low- versus high-skilled) and hence the supply of skills to the labor market; second, the different skill types and capital in the form of machines interact in production subject to a finite elasticity of substitution so that their marginal products reflect both underlying capabilities and relative scarcity; and third, the effective human capital commanded by the different skill types can be affected via (public) spending on the education system. Hence, there is a rich menu for possible fiscal interventions to address the policy challenges posed by automation. At the same time, however, the relevant interactions are complex and call for an integrated assessment of the tax and spending components of public policy.

In addition to these theoretical considerations, our emphasis on human capital and education spending is also motivated by empirical observations on the effects of education policy on wage inequality between low- and high-skilled workers. Using data for the EU-27 countries, the United States and Japan, we examine the relationship between public education spending and skill premia as measured by the ratio of wages of workers with at least a college education relative to those of workers without college education.¹ Controlling for country fixed effects, private education spending, and including country-specific linear time trends (which capture, among other things,

¹Wage data are from the EUKLEMS 2022 release; education spending data are from the OECD.

the changing pattern of technical change over time), we find that the relation between public education spending and wage inequality is significantly positive and driven mostly by higher education spending (see Table 3 in the Appendix). A similar result holds also for a panel of US states where education spending per student is positively associated with several measures of inequality measures (Table 4 in the Appendix).

This empirical pattern is at odds with a situation where more generous education spending encourages skill acquisition only along the extensive margin, as skilled labor should then become relatively abundant, which would lead to a compression of the wage distribution. We therefore conceptualize the effects of education spending to work both along the extensive margin (via the enrollment decision in higher education) and along the intensive margin (via the extent of human capital formation while in education). In addition, we consider a *hierarchical public education system* with a sequential process for basic and higher education. Accordingly, the human capital of low-skilled workers is determined only by public spending on basic education, whereas the human capital of high-skilled workers depends on both the spending on higher education and the human capital previously acquired through basic education.

Against this background, we examine the options for fiscal policy in a growth model where both technology and human capital are endogenous. We conduct our analysis building on the model considered in Prettnner and Strulik (2020). This model encompasses automation, capital-skill complementarity, endogenous educational choices, and R&D-driven growth along the lines of Jones (1995, 2022). Automation takes the form of an increase in the productivity of machines that substitute for low-skilled workers and complement high-skilled workers. Since education is endogenous, the supply of high- and low-skilled workers depends on the skill premium and on the government’s fiscal policy. The key feature amended to this framework is the hierarchical education system discussed above. Publicly funded education spending can therefore augment workers’ human capital in two stages. Whereas all workers benefit from spending on basic (primary and secondary) education, only those who sort into higher education (namely the high-skilled workers) get the additional benefit from higher (college) education.²

Fiscal policy influences the dynamics of the economy, with important effects on growth and inequality. Taxation happens via a linear tax on wage income and/or via a *robot tax*, that is, an ad-valorem tax on machines. On the spending side, the government can use the revenues for redistributive transfer payments and/or spending on education at the two respective tiers. Hence, as spending plays a role not only used for redistribution but also for the formation of human capital, it is important to assess fiscal policy in an integrated fashion, that is, by examining the effect of tax policies while taking into account also the effects of the public spending on transfers and education they finance.

²In extensions to our baseline model, we also allow for private human capital enhancing spending by high-skilled individuals, and for public spending targeted at low-skilled individuals after they have completed basic education.

In a partial equilibrium exercise, in which we keep both the individual (intensive-margin) labor supply and the aggregate (extensive-margin) supply of high- and low-skilled labor constant, we disentangle the two different channels through which a change in taxation affects inequality: the redistribution and the human capital channel. Both these channels materialize because the revenue raised from taxation is recycled back to the economy in the form of either transfer payments and/or education spending. While the redistribution channel, by transferring resources from richer households (high-skilled workers) to poorer households (low-skilled workers), directly reduces inequality, the human capital channel has the opposite effect since the education system benefits proportionally more the high-skilled workers. We find that the magnitude of these effects through the different channels crucially depends on the way redistributive transfers and education spending are financed. The redistribution channel is, indeed, stronger if government spending is financed through a robot tax, and, vice versa, the human capital channel is stronger through a labor tax. This is because the robot tax directly affects the high-skilled workers as complements to machines, while the linear labor tax affects high- and low-skilled workers proportionally.³

Since the two channels work in opposite directions, the net effect of taxation on inequality is generally ambiguous and can only be determined when the mix of the government's tax and spending is known. Calibrating the model – and in particular the breakdown of fiscal policy – with US data and now admitting also responses along the intensive and the extensive margin for the supply of skills to the labor market, we observe that, following an increase in the labor tax, both economic growth and inequality increase, while after an increase in the robot tax, the effect on economic growth and inequality is opposite. In other words, given the structure of the US economy and the allocation of fiscal revenue for transfer payments and education funding, we find that, for the labor tax, the human capital channel dominates the redistribution channel; for the robot tax, the dominance is reversed.

We then use the calibrated model to examine the effects of different policies on growth and inequality. Starting from the calibrated configuration of fiscal policy, we find that no one-dimensional change of policy is able to increase growth without increasing inequality (or reduce inequality without harming growth). Indeed, each of these policies entails a fundamental trade-off between economic growth and inequality: a policy aimed at reducing inequality also reduces the incentives to acquire higher education, while a policy aimed at increasing growth creates higher incentives to acquire college education leading to higher inequality. However, we identify conditions for mixed (two-dimensional) policies to achieve both higher growth and lower inequality. For instance, by changing the tax schedule, we observe that a joint increase in the robot tax (which reduces inequality) and in the labor tax (which increases growth via the human capital channel) can lead to both higher economic growth and lower inequality. This result highlights the relevance of accounting for

³Notice, however, that the transfer payments can render the fiscal system progressive (or regressive) even under the linear tax considered here.

endogenous human capital accumulation. In the model with exogenous human capital, indeed, a joint increase of both labor and robot tax would always lead to a reduction in production due to the lack of education spending fostering human capital.

Although it is possible to both increase economic growth and reduce inequality relative to the initially calibrated situation with a mix of policies leading to a welfare-improving outcome, the welfare-maximizing policy mix is not necessarily one that leads to both higher growth and lower inequality. This is because the optimal policy mix depends on the planner preference for inequality relative to growth. Hence, depending on the planner preference, the optimal policy mix can consist of any set of policies leading to either higher growth, lower inequality, or both. This motivates a normative exercise where we (i) determine the optimal tax schedule in terms of labor and robot tax as the preference of the planner change, and (ii) analyze its dynamic evolution given a utilitarian welfare function. For this case we observe that the government should initially reduce the robot tax significantly and compensate the loss in revenues with a higher labor tax. Subsequently, the government should progressively increase the robot tax and reduce the labor tax over time. The rationale behind these dynamics is that the initially low robot tax creates incentives to engage in R&D, which enhances machine productivity and thus economic growth. As machine productivity increases and the skill premium widens, the government then finds it optimal to increase the robot tax and reduce the labor tax since the robot tax has stronger redistribution effects and thus works to reduce inequality.

This finding differs from the Chamley-Judd result of an optimal zero capital tax in the long-run. The reason is that capital in our model is represented by automated machines (robots) that perfectly substitute for low-skilled workers who are not, therefore, harmed by the robot tax. Hence, the robot tax can optimally be positive as it reduces inequality through transfers. However, since a robot tax has a direct negative effect on growth, in a model with exogenous human capital, the optimal robot tax is very small or zero. With endogenous human capital formation, instead, the robot tax has also a positive effect on growth through the human capital channel, justifying a higher optimal level of the tax. Finally, since the robot tax is a redistributive tax reducing inequality, while the labor tax benefits mostly the high-skilled workers, the government optimally increases the robot tax and reduces the labor tax over time.

Related Literature Our paper contributes to several strands of the literature. To begin, we add to the growing body of research on the effects of automated technologies on growth and inequality. Investigating capital-skill complementarity as a mechanism generating inequality, our paper follows the lead of [Krusell et al. \(2000\)](#). Our particular focus on the role of (higher) education in the context of increased adoption of automated technologies is shared with [Goldin and Katz \(2010\)](#), [Goldin et al. \(2020\)](#) and [Acemoglu et al. \(2012\)](#). Also related are contributions by [Brynjolfsson and McAfee \(2011\)](#), [Frey and Osborne \(2017\)](#), [Graetz and Michaels \(2018\)](#), [Acemoglu and Restrepo \(2020\)](#) who

highlight the negative consequences of automation on wages and employment for workers with lower education. Most of these papers analyze the effect of the introduction of automation technologies on inequality along the skill distribution assuming an exogenous supply of high- and low-skilled workers. Following [Prettner and Strulik \(2020\)](#), we consider endogenous education choices which partially offset the adverse effect of automation on inequality by endogenously increasing the supply of high-skilled workers as the skill-premium increases due to automation. However, differently from this paper, we proceed with a deeper analysis of the effect of education on growth and inequality by allowing the government to affect the human capital of the agents through education spending.

Our paper, indeed, also contributes to the literature on human capital accumulation and growth. [Guvenen et al. \(2013\)](#) study the role of taxation for human capital formation via a generic accumulation equation. Instead, we follow the literature on public education finance ([Blankenau, 2005](#); [Arclean and Schiopu, 2010](#)) and model a hierarchical education system in which basic education spending affects all workers, while college education spending affects only high-skill workers. Differently from their paper, we highlight the relevance of such an education system on inequality in a setting with endogenous R&D and automation and analyze the implications of fiscal policies on both economic growth and inequality through the human capital channel.

Given the prominence of human capital in our model, our work also connects to the theoretical and quantitative literature examining the joint properties of optimal (linear) tax and education policies. [Krueger and Ludwig \(2013\)](#) and [Krueger and Ludwig \(2016\)](#) characterize the optimal mix of progressive income taxes and education subsidies in an overlapping generations model with endogenous human capital and idiosyncratic income risk under incomplete financial markets and find that the welfare-maximizing fiscal policy features a progressive labor income tax code combined with a sizable subsidy for college education. This highlights the complementarity between the redistributive (and insurance) role of progressive taxation and appropriate education subsidies to offset the tax-induced labor supply distortions along the intensive and extensive margin ([Bénabou, 2002](#)).⁴

Finally, our work is related to the literature analyzing the implications of fiscal policies on growth. In particular, we refer to the recent and growing literature on robot and capital taxation ([Guerreiro et al., 2022](#); [Thuemmel, 2022](#); [Jacobs and Thuemmel, 2020](#)). Similar to [Guerreiro et al. \(2022\)](#), we show that the optimal robot tax can be different from zero. However, while in their paper this is driven by the presence of older workers in the labor market who are constrained by their initial education choices, in our model the positive robot tax reflects that its redistributive role is accompanied by its growth-enhancing effect through the human capital channel. Moreover,

⁴[Lans Bovenberg and Jacobs \(2005\)](#) have coined the term ‘Siamese twins’ to describe this complementarity. On the other hand, the effect of education policy on the relative supply of skills may lead to changes in the college premium between skilled and unskilled wages; this mechanism (the so-called Stiglitz effect) can potentially justify a reduction in tax progressivity, so that the two policies might be substitutes.

in contrast to their paper which finds that the optimal robot tax is zero in the long-run, our model suggests a progressive increase in the robot tax over time as an efficient way to reduce growing wage inequality. Another recent contribution on this topic is [Acemoglu et al. \(2020a\)](#) in which the authors argue that the US tax system is biased against labor and in favor of capital suggesting that moving to the optimal taxation of capital and labor would have positive effects on employment and the labor share. Differently from their paper, we find that, owing to its effects on skills and technology over time, the optimal robot tax should initially be reduced relative to the current situation and only later be increased.

More generally, given the fundamental importance of the equity-efficiency trade-off for the appropriate design of fiscal policy in our model, it is also useful to position our work within the context of the public finance literature on optimal taxation following [Mirrlees \(1971\)](#) and [Diamond and Mirrlees \(1971\)](#). There, information frictions constrain the government’s tax and transfer system not to discriminate across unobservable types. In the particular two type-case of ‘skilled’ versus ‘unskilled’ workers considered in [Stiglitz \(1982\)](#), production efficiency (and thus a zero robot tax) is optimal when worker types are exogenous and they enter production as perfect substitutes. With imperfect substitutability across types, this is no longer the case, provided labor supply distortions along the intensive margin are the relevant concern. But adding an extensive margin via skill acquisition tends to restore the optimality of production efficiency, that is, the absence of robot taxes.⁵ By contrast, in our economy, worker types are observable so that the tax and transfer system can condition on skills in a discriminatory way. Imperfect substitutability in production and endogenous skill acquisition, though, are shared features in both environments. In addition, in our economy workers’ wages are endogenous not only due to interaction in production, but also due to the human capital generated via the government’s tax-financed education policy. This justifies deviations from production efficiency via positive robot taxes. Over time, this motive actually becomes stronger because of the skill-biased nature of the technological progress which is endogenously generated in our model.⁶

The rest of this paper is structured as follows. In the next section, we present the model before Section 3 proceeds with a partial equilibrium analysis in which we analyze the effect of a change in taxation and highlight the main channels at play. In Section 4, we present the general equilibrium dynamics of the model based on the calibration to US data. In Section 5, we discuss the implications of exogenous changes in fiscal policy, contrasting interventions via a single instrument only, and

⁵For example, in [Guerreiro et al. \(2022\)](#) positive robot taxes are optimal only in the transition while initial old generations, whose skill choices are predetermined, are still active in production. Once they retire, the extensive margin (skill supply) decisions of subsequent young generations are the key constraint for policy, thus prescribing zero robot taxes.

⁶[Slavík and Yazici \(2014\)](#) also establish the optimality of positive (differential) capital taxes, though in an environment with exogenous skills and no technical progress.

joint changes of two instruments at a time. Section 6 examines the dynamics of the optimal tax schedule over time and its dependence on the planner’s relative weight on low-skilled versus high-skilled workers. Moreover, we provide a decomposition of the relevant role in shaping the pattern of optimal taxes of adjustments in the supply of skills along the intensive and the extensive margin, as well as in the overall progressivity of fiscal policy. In Sections 7 and 8, we extend the baseline model to encompass, respectively, private education spending on higher education and education policies targeted at low-skilled individuals (e.g., in the form of on-the-job training). Finally, Section 9 concludes.

2 Model

Similar to [Prettner and Strulik \(2020\)](#), we consider an overlapping generation economy in which individuals live for two periods. Having completed basic (i.e., primary and secondary) education, individuals enter the economy as young adults with a unit endowment of time. They then decide whether or not to spend a certain (fixed) fraction of their time studying to obtain higher (i.e., tertiary/college) education. If they decide against higher education, individuals allocate their full unit time endowment between leisure and labor as low-skilled workers. If they spend time in higher education, they allocate their remaining time between leisure and labor as high-skilled workers. Hence, higher education is associated with an opportunity cost in terms of reduced marketable time; on the other hand, it augments individuals’ human capital and endows them with skills that differentiate them from unskilled workers. Both types of workers use their labor market income for consumption and savings for their second period of life when they are retired and simply consume the return to their savings. After the second period, individuals die with certainty. Time t evolves discretely, each period corresponding to one generation. The population size is constant in every period and equal to N .

Individuals are heterogeneous with respect to their ability to complete a college degree, which affects education decisions via the disutility (of effort) while in higher education. In consequence, each generation is partitioned into two groups: those who opt into higher education and become high-skilled workers, and those who do not and become low-skilled workers. The two groups are distinct both in their human capital and the way they interact with machines in production. Low-skilled workers are employed in the final goods sector and are perfect substitutes to machines. By contrast, high-skilled workers are employed either in the final goods sector as complements to machines, or in the R&D sector for developing the footprints for machines that are used in the final goods sector.

The government raises taxes through a labor tax (linear tax on wage income) and a robot tax (ad-valorem tax on the use of machines in the final goods sector) and uses the revenue to finance expenditure on education and transfers. Education spending is allocated to basic education

and higher education. While basic education spending affects the human capital of both low-skilled and high-skilled workers, higher education spending directly affects only the human capital of high-skilled workers. Transfers can be differentiated across worker types and thus facilitate redistribution.

2.1 Households

Individuals obtain utility from consumption and leisure, and disutility from completing higher education. Lifetime utility of an agent of type $j \in \{H, L\}$ is given by

$$\mathcal{U}_{j,t} = \log(c_{j,t}) + \beta \log(\bar{R}s_{j,t}) + \gamma \log(z_{j,t}) - \mathbb{1}_{[j=H]} v(a), \quad (1)$$

where $c_{j,t}$ is the consumption of the young agent in period t , β is the discount factor, $\bar{R}s_{j,t}$ is the consumption of the old agent in period $t+1$ (consisting of savings $s_{j,t}$ and gross interest payments \bar{R}), $\gamma > 0$ is a preference weight, and $z_{j,t}$ is leisure. We make the simplifying assumption of a small and open economy such that the interest rate \bar{R} is determined on the world capital market and, therefore, exogenously given. The last term in (1) is the effort cost from higher education. Individuals are heterogeneous in terms of their (innate) ability a . Individuals with a higher ability suffer lower effort costs from completing higher education, i.e., $\partial v / \partial a \leq 0$. In particular, we assume

$$v(a) = \begin{cases} \psi_1 \cdot \log(\frac{\psi_2}{a-\underline{a}}), & \text{if } a \geq \underline{a} \\ \infty, & \text{if } a < \underline{a} \end{cases}$$

where $\psi_1 > 0$ and $\psi_2 > 0$ determine level and slope of the effort cost, and $\underline{a} > 0$ captures the idea that not all agents are able to obtain a college degree.

Given their innate ability level a , individuals maximize their lifetime utility by choosing consumption, savings, and leisure in period t subject to the following budget constraint,

$$(1 - \tau_W)(1 - \eta_j - z_{j,t})w_{j,t} + \hat{T}_{j,t} = c_{j,t} + s_{j,t},$$

where τ_W represents the linear tax rate on wage income, η_j is the time spent to acquire higher education, which is equal to zero for agents who do not go to college ($\eta_L = 0$) and equal to $\eta > 0$ for agents obtaining a college degree ($\eta_H = \eta$), $w_{j,t}$ is the type-specific wage and $\hat{T}_{j,t}$ is the per-capita transfer to an agent of type j .⁷ As old individuals do not work, they only consume their savings.

⁷Given a total volume of transfers $T_{j,t}$ to young individuals of type j , the per-capita payments are computed as $\hat{T}_{L,t} \equiv T_{L,t}/L_t$ and $\hat{T}_{H,t} \equiv T_{H,t}/H_t$, where L_t and H_t denote the mass of low- and high-skilled workers, respectively. Notice also that per-capita transfers are not restricted to be uniform across types, so that the tax-and-transfer system can be progressive (or regressive) even under linear taxation.

From the household utility maximization problem, we obtain

$$c_{j,t} = \frac{1}{1 + \beta + \gamma} \left((1 - \tau_W)(1 - \eta_j)w_{j,t} + \hat{T}_{j,t} \right), \quad (2)$$

$$s_{j,t} = \frac{\beta}{1 + \beta + \gamma} \left((1 - \tau_W)(1 - \eta_j)w_{j,t} + \hat{T}_{j,t} \right), \quad (3)$$

$$z_{j,t} = \frac{\gamma}{(1 + \beta + \gamma)(1 - \tau_W)w_{j,t}} \left((1 - \tau_W)(1 - \eta_j)w_{j,t} + \hat{T}_{j,t} \right). \quad (4)$$

Note that the savings rate (out of potential income), $\frac{\beta}{1 + \beta + \gamma}$, is constant over time and not type-specific. Given the ability level a , an individual decides to go to college to acquire higher education if $\mathcal{U}_{H,t}(a) \geq \mathcal{U}_{L,t}(a)$. Hence, there exists a threshold level a_t^* such that if $a \geq a_t^*$ the individual attends college, and if $a < a_t^*$ the individual does not. By solving the indifference condition $\mathcal{U}_{H,t}(a) = \mathcal{U}_{L,t}(a)$, we obtain

$$a_t^* = \psi_2 \left(\frac{c_{H,t}}{c_{L,t}} \right)^{-\frac{1 + \beta + \gamma}{\psi_1}} \left(\frac{w_{H,t}}{w_{L,t}} \right)^{\frac{\gamma}{\psi_1}} + a. \quad (5)$$

Assuming that individual ability a is distributed according to a cumulative distribution function F , this implies that the mass of high-skilled workers is given by $H_t = (1 - F(a_t^*)) \cdot N$ and the number of low-skilled workers is given by $L_t = F(a_t^*) \cdot N$.

2.2 Final goods sector

Aggregate output is produced according to the following production function,

$$Y_t = \left(h_{H,t} \tilde{H}_{Y,t} \right)^{1 - \alpha} \left(\left(h_{L,t} \tilde{L}_t \right)^\alpha + \sum_{i=1}^{A_t} x_{i,t}^\alpha \right), \quad (6)$$

where $\tilde{H}_{Y,t}$ is high-skilled labor employed in the final goods sector, \tilde{L}_t is low-skilled labor, $h_{j,t}$ is the human capital of an agent of type j at time t , $x_{i,t}$ are machines of type i , $\alpha \in (0, 1)$ is the elasticity of output with respect to (effective) labor that can be easily automated, and A_t represents the technological frontier. Let $p_{i,t}$ denote the price of one unit of machine of type i and τ_R the ad-valorem tax on machines (the robot tax). The problem faced by competitive final goods firms then is

$$\max_{\{\tilde{H}_{Y,t}, \tilde{L}_t, \{x_{i,t}\}_{i=1}^{A_t}\}} Y_t - w_{H,t} \tilde{H}_{Y,t} - w_{L,t} \tilde{L}_t - (1 + \tau_R) \sum_{i=1}^{A_t} p_{i,t} x_{i,t},$$

from which factor prices are obtained as

$$w_{H,t} = (1 - \alpha) \left(h_{H,t} \tilde{H}_{Y,t} \right)^{-\alpha} h_{H,t} \left((h_{L,t} \tilde{L}_t)^\alpha + \sum_{i=1}^{A_t} x_{i,t}^\alpha \right), \quad (7)$$

$$w_{L,t} = \alpha \left(\frac{h_{H,t} \tilde{H}_{Y,t}}{h_{L,t} \tilde{L}_t} \right)^{1 - \alpha} h_{L,t}, \quad (8)$$

$$(1 + \tau_R) p_{i,t} = \alpha \left(\frac{h_{H,t} \tilde{H}_{Y,t}}{x_{i,t}} \right)^{1 - \alpha}. \quad (9)$$

2.3 R&D sector

The R&D sector produces the blueprints for new machines by employing only high-skilled labor. Similar to [Romer \(1990\)](#) and [Jones \(1995\)](#), we consider the following process for expanding the technological frontier via R&D,

$$A_t - A_{t-1} = \bar{\delta}_t h_{H,t} \tilde{H}_{A,t}, \quad (10)$$

where $\tilde{H}_{A,t}$ represents high-skilled labor employed in the R&D sector, $\bar{\delta}_t \equiv \delta \frac{(A_{t-1})^{\lambda_1}}{(h_{H,t} \tilde{H}_{A,t})^{1-\lambda_2}}$ is a measure of the productivity in the R&D sector capturing intertemporal knowledge spillovers (measured by $\lambda_1 \in (0, 1]$) and congestion externalities (measured by $(1 - \lambda_2)$ with $\lambda_2 \in [0, 1]$), and δ is a scaling parameter.⁸ R&D firms' profits are given by the revenues generated by selling patents net of labor costs, $p_{A,t} \bar{\delta}_t h_{H,t} \tilde{H}_{A,t} - w_{A,t} \tilde{H}_{A,t}$, where $p_{A,t}$ denotes the price of blueprints and $w_{A,t}$ is the wage rate in the R&D sector. Optimality requires that $w_{A,t} = p_{A,t} \bar{\delta}_t h_{H,t}$. Patent protection is assumed to last for one model period.

2.4 Intermediate goods sector

The intermediate goods sector rents capital to produce machines. We consider a linear technology, $x_{i,t} = k_{i,t}$, where $k_{i,t}$ is the amount of capital used by the intermediate producer manufacturing machine of type i . We assume that physical capital depreciates fully within one model period. There are two types of firms in the intermediate goods sector. Given the patent duration of one period, producers of older vintage machines (denoted by m) do not need to acquire patents, but operate under perfect competition; free entry then implies zero-profits, i.e., $\pi_{m,t} = 0$. By contrast, producers of the latest vintage machines (denoted by n) use patents from the R&D sector as input, which endows them with a certain degree of market power; free entry into the sector then implies that the profits $\pi_{n,t}$ for the producers of the latest vintage machines must be equal to the patent costs, i.e., $\pi_{n,t} = p_{A,t}$. The profit maximization problem faced by latest vintage machines producers is

$$\max_{x_{n,t}} p_{n,t}(x_{n,t}) x_{n,t} - \bar{R} x_{n,t}$$

subject to equation (9). Optimality requires:

$$\frac{\partial p_{n,t}(x_{n,t})}{\partial x_{n,t}} \frac{x_{n,t}}{p_{n,t}} + 1 = \frac{\bar{R}}{p_{n,t}} \iff p_{n,t} = \frac{\bar{R}}{\alpha} \iff \pi_{n,t} = \frac{1-\alpha}{\alpha} \bar{R} x_{n,t},$$

from which the supply of machines of the latest vintage is obtained as

$$x_t \equiv x_{n,t} = \left(\frac{\alpha^2}{\bar{R}(1 + \tau_R)} \right)^{\frac{1}{1-\alpha}} h_{H,t} \tilde{H}_{Y,t}. \quad (11)$$

Older vintage machines producers, instead, face the following problem,

$$\max_{x_{m,t}} p_{m,t} x_{m,t} - \bar{R} x_{m,t},$$

⁸Productivity in the R&D sector, $\bar{\delta}_t$, is taken to be external to each individual firm.

from which we obtain the optimality condition $p_{m,t} = \bar{R}$ and the supply of machines of older vintage,

$$x_{m,t} = \left(\frac{\alpha}{\bar{R}(1 + \tau_R)} \right)^{\frac{1}{1-\alpha}} h_{H,t} \tilde{H}_{Y,t}. \quad (12)$$

Combining (11) and (12), we obtain $x_{m,t} = \alpha^{\frac{1}{\alpha-1}} x_{n,t}$. Finally, aggregating over all vintages, we can rewrite the final goods production function as

$$Y_t = \left(h_{H,t} \tilde{H}_{Y,t} \right)^{1-\alpha} \left(\left(h_{L,t} \tilde{L}_{L,t} \right)^\alpha + \tilde{A}_t x_t^\alpha \right),$$

where $\tilde{A}_t \equiv \left(\alpha^{\frac{\alpha}{\alpha-1}} - 1 \right) A_{t-1} + A_t$.⁹

2.5 Human capital

Human capital formation takes place via education, the effectiveness of which is determined by the amount and composition of public education spending, E_t .¹⁰ Following the literature on public education finance,¹¹ we assume a hierarchical public education system with a sequential process for basic and higher education. Accordingly, basic human capital, $h_{B,t}$, is determined only by public spending on basic education, $E_{B,t}$, while the human capital of high-skilled workers, $h_{H,t}$, depends on both the spending on higher education, $E_{H,t}$, and the human capital previously acquired through basic education, $h_{B,t}$. Total public education spending is the sum of the expenditures across the two tiers,

$$E_t = E_{B,t} + E_{H,t}.$$

Basic human capital $h_{B,t}$ and human capital of the low-skilled workers $h_{L,t}$ coincide, as there is no possibility to further augment the human capital of (low-skilled) workers entering the labor market with only primary and secondary education,¹²

$$h_{L,t} = h_{B,t} = B \cdot \hat{E}_{B,t}^{\mu_B},$$

where $\hat{E}_{B,t} \equiv E_{B,t}/N$ is the per-capita level of public education spending for basic education. Building on the human capital acquired from basic education, those individuals selecting into higher education acquire additional skills, which (i) differentiate them from unskilled-workers and (ii) raise their human capital to a higher level. Specifically, we assume

$$h_{H,t} = B_H \cdot h_{B,t}^{1-\mu_H} \cdot \hat{E}_{H,t}^{\mu_H},$$

⁹Indeed, $\sum_{i=1}^{A_t} x_{i,t}^\alpha = A_{t-1} x_{m,t}^\alpha + (A_t - A_{t-1}) x_{n,t}^\alpha = \left(\left(\alpha^{\frac{\alpha}{\alpha-1}} - 1 \right) A_{t-1} + A_t \right) x_t^\alpha = \tilde{A}_t x_t^\alpha$.

¹⁰In Section 7, we extend the baseline model to feature also private spending on higher education.

¹¹See e.g.

¹²In Section 8, we relax this assumption by introducing a role for post-graduation education spending targeted at low-skilled individuals, so that $h_{L,t} \neq h_{B,t}$. A prime example for such expenditures are on-the-job training measures that increase the productivity of low-skilled workers and make them more competitive to machines in the final production sector.

where $\hat{E}_{H,t} \equiv E_{H,t}/H_t$ is the per-capita level of public education spending for higher education. The parameters $B > 0$ and $B_H > 0$ are productivity parameters, while $\mu_B \in (0, 1)$ and $\mu_H \in (0, 1)$ govern the elasticity of human capital formation to public spending inputs at the basic and higher level, respectively. Notice that the above specification of human capital formation entails a role for public education spending via both the extensive margin (by drawing a larger number of individuals into higher education) and the intensive margin (by making education at both tiers more productive).

2.6 Fiscal policy

The government runs a balanced budget, so that, in each period, the expenditures for public education spending and transfers are equal to tax revenues.

Tax revenues The government imposes linear taxes on factor income from labor and machines. Total tax revenues, \mathcal{G}_t , are therefore given by

$$\mathcal{G}_t = \mathcal{G}_{W,t} + \mathcal{G}_{R,t},$$

where the revenues from taxing labor and machines, respectively, are

$$\begin{aligned} \mathcal{G}_{W,t} &= \tau_W \left(w_{H,t} \tilde{H}_{Y,t} + w_{A,t} \tilde{H}_{A,t} + w_{L,t} \tilde{L}_t \right), \\ \mathcal{G}_{R,t} &= \tau_R \sum_{i=1}^{A_t} p_{i,t} x_{i,t} = \tau_R \hat{A}_t \bar{R} x_t, \end{aligned}$$

with x_t denoting the latest vintage technology and $\hat{A}_t \equiv \alpha^{\frac{1}{\alpha-1}} A_{t-1} + \alpha^{-1} (A_t - A_{t-1})$.¹³

Spending On the spending side, tax revenues are used to finance public education, E_t , and transfers, T_t . Budget balance implies

$$\mathcal{G}_t = E_t + T_t.$$

For our subsequent analysis, we express public education spending as a fraction $\phi_t \in (0, 1]$ of total government spending,

$$E_t = \phi_t \cdot \mathcal{G}_t.$$

Public spending on basic education, in turn, is expressed as a fraction $\phi_{B,t} \in (0, 1)$ of total public education spending,

$$\begin{aligned} E_{B,t} &= \phi_{B,t} \cdot E_t, \\ E_{H,t} &= (1 - \phi_{B,t}) \cdot E_t. \end{aligned}$$

¹³Indeed, $\sum_{i=1}^{A_t} p_{i,t} x_{i,t} = A_{t-1} \bar{R} x_{m,t} + (A_t - A_{t-1}) \frac{\bar{R}}{\alpha} x_{n,t} = (\alpha^{\frac{1}{\alpha-1}} A_{t-1} + \alpha^{-1} (A_t - A_{t-1})) \bar{R} x_t = \hat{A}_t \bar{R} x_t$.

Similarly, we capture total transfers as a share of total government spending ($T_t = (1 - \phi_t) \cdot \mathcal{G}_t$), and the share of transfers going to low-skilled individuals as a fraction, $\omega_t \in [0, 1]$ of total transfers,

$$\begin{aligned} T_{L,t} &= \omega_t \cdot T_t, \\ T_{H,t} &= (1 - \omega_t) \cdot T_t. \end{aligned}$$

2.7 Competitive equilibrium

For a given balanced-budget fiscal policy $\{\tau_W, \tau_R, \phi, \phi_B, \omega\}_t$, a competitive equilibrium is given by an allocation and prices such that (i) the household problem (including the education decision) and the firm problem in the intermediate, final and R&D sector are solved; (ii) the markets for low-skilled and high-skilled labor and the markets for machines, final goods and patents clear. In particular, the population constraint $N = H_t + L_t$ holds, and the total number of high-skilled workers is distributed to production and R&D, $H_t = H_{Y,t} + H_{A,t}$, such that their respective wage rates are equalized, $w_{H,t} = w_{A,t}$.¹⁴

3 Partial equilibrium analysis

Before turning to the model analysis for a calibrated environment, this section examines the main channels through which a change in taxation affects inequality. Key to our results is the fact that taxation generates fiscal revenues, which are used not only for transfer payments but also for public education. In consequence, tax policy affects inequality via its redistributive effects and its effects on human capital formation. To highlight these effects, we proceed with a partial equilibrium analysis, keeping the aggregate supply of skills constant both along the extensive margin (education choice) and the intensive margin (labor supply). This is achieved by fixing the ability threshold a^* for selecting into higher education and considering the case of constant individual labor supply ($\gamma = 0$).¹⁵ As a measure of inequality, we consider the consumption ratio between high- and low-skilled workers,

$$\frac{c_H}{c_L} = \frac{(1 - \tau_W)(1 - \mu)w_H + \hat{T}_H}{(1 - \tau_W)w_L + \hat{T}_L}.$$

As hinted above, taxation affects the consumption ratio through two main channels: the *redistribution channel* (RE) and the *human capital channel* (HC). The redistribution channel accounts for the direct effect of taxes on disposable income and transfers, while the human capital channel

¹⁴The equilibrium conditions are detailed in the Appendix.

¹⁵For the rest of this section, we drop time subscripts as they are not necessary for the analysis.

accounts for the effect of education spending on wages through human capital,

$$\begin{aligned}\frac{d c_H/c_L}{d \tau_W} &= \underbrace{\frac{\partial c_H/c_L}{\partial \tau_W} + \sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \tau_W}}_{\frac{d c_H/c_L}{d \tau_W} \Big|_{\text{RE}}} + \underbrace{\sum_{j \in H,L} \left(\frac{\partial c_H/c_L}{\partial w_H} \frac{\partial w_H}{\partial h_j} + \frac{\partial c_H/c_L}{\partial w_L} \frac{\partial w_L}{\partial h_j} \right) \frac{\partial h_j}{\partial \tau_W}}_{\frac{d c_H/c_L}{d \tau_W} \Big|_{\text{HC}}}, \\ \frac{d c_H/c_L}{d \tau_R} &= \underbrace{\frac{\partial c_H/c_L}{\partial w_H} \frac{\partial w_H}{\partial \tau_R} + \sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \tau_R}}_{\frac{d c_H/c_L}{d \tau_R} \Big|_{\text{RE}}} + \underbrace{\sum_{j \in H,L} \left(\frac{\partial c_H/c_L}{\partial w_H} \frac{\partial w_H}{\partial h_j} + \frac{\partial c_H/c_L}{\partial w_L} \frac{\partial w_L}{\partial h_j} \right) \frac{\partial h_j}{\partial \tau_R}}_{\frac{d c_H/c_L}{d \tau_R} \Big|_{\text{HC}}}.\end{aligned}$$

Redistribution channel Within the redistribution channel, we can identify distinct mechanisms through which taxation affects consumption inequality. Considering a marginal increase in the labor tax τ_W , we can distinguish three effects: (i) the direct negative effect on *disposable income*, $\text{RE}_W(1)$; (ii) the *tax rate* effect via increased transfers financed as wages are taxed at a higher rate, $\text{RE}_W(2)$; and (iii) the *tax base* effect via increased transfers financed as higher education spending augments human capital and thus wages, $\text{RE}_W(3)$:

$$\frac{d c_H/c_L}{d \tau_W} \Big|_{\text{RE}} = \underbrace{\frac{\partial c_H/c_L}{\partial \tau_W}}_{\text{RE}_W(1)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_W}}_{\text{RE}_W(2)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j' \in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j'' \in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_W}}_{\text{RE}_W(3)}.$$

We can show that

$$\frac{d c_H/c_L}{d \tau_W} \Big|_{\text{RE}} < 0 \quad \Longleftrightarrow \quad \omega > \frac{w_L L_L}{w_L L_L + w_H (1 - \eta) L_H} \equiv \tilde{\omega}. \quad (13)$$

Accordingly, the redistribution channel works to reduce consumption inequality if the share of transfers given to low-skilled workers is sufficiently high, namely exceeding their relative share of labor income. Intuitively, this means that if the low-skilled workers get more transfers than their contribution to the government budget through labor taxes, then their relative consumption increases.¹⁶

Consider now a marginal change in the robot tax τ_R . As for the labor tax, we can distinguish three effects: (i) the effect on high skilled workers' wages and consumption arising due to their *complementarity* in production to machines, $\text{RE}_R(1)$; (ii) the *tax rate* effect, $\text{RE}_R(2)$, and (iii) the *tax base* effect, $\text{RE}_R(3)$, which unfold in analogy to the case of the labor tax:

$$\frac{d c_H/c_L}{d \tau_R} \Big|_{\text{RE}} = \underbrace{\frac{\partial c_H/c_L}{\partial w_H} \frac{\partial w_H}{\partial \tau_R}}_{\text{RE}_R(1)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_R}}_{\text{RE}_R(2)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j' \in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j'' \in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_R}}_{\text{RE}_R(3)}.$$

¹⁶ As $\text{RE}_W(3)$ rests on the interaction of human capital and transfers, it could in principle also be subsumed under the human capital channel. Under exogenous human capital $\text{RE}_W(3)$ disappears; condition (13) holds identically also in this case.

As for the labor tax, $RE_R(2)$ and $RE_R(3)$ are negative if low-skilled workers obtain proportionally more transfers relative to their labor income share than the high-skilled workers, i.e., if $\omega > \tilde{\omega}$. However, differently from the labor tax, $RE_R(1)$ is always negative since the robot tax affects disposable income not uniformly across the two skill groups, but instead has a direct negative effect only the wages of the high-skilled workers and has no direct effect on the wages of the low-skilled workers. This implies that $\omega > \tilde{\omega}$ is a sufficient (but not necessary) condition for the redistribution channel to reduce inequality through a change in the robot tax. Since this condition is sufficient for the redistribution effect to reduce consumption inequality through τ_R , while it is a necessary condition for τ_W , the robot tax is actually more redistributive. Intuitively, since the robot tax only directly affects the wages of the high-skilled workers, while the labor tax has a symmetric direct effect on the wages of low- and high-skilled workers, the robot tax has a stronger redistributive effect. We can summarize these results with the following proposition.

Proposition 3.1. *An increase in taxation reduces consumption inequality, c_H/c_L , through the redistribution channel (RE) if $\omega > \tilde{\omega}$. This is a necessary condition for the linear labor tax τ_W and a sufficient condition for the ad-valorem robot tax τ_R .*

Human capital channel To highlight the human capital channel, we abstract from transfers by assuming $\phi = 1$.¹⁷ The consumption ratio then simplifies to

$$\frac{c_H}{c_L} = (1 - \eta) \frac{w_H}{w_L},$$

i.e., it only depends on the wage ratio. Within the human capital channel, considering a marginal increase of either labor or robot taxes, we can distinguish two mechanisms: (i) the direct human capital effect on wages via increased *education spending* financed by taxation, $HC_g(1)$; and (ii) the additional human capital effect on wages via increased *R&D activity* and machine intensity \tilde{A} , $HC_g(2)$. Specifically, for $g \in \{W, R\}$, we have:

$$\left. \frac{d w_H/w_L}{d \tau_g} \right|_{\text{HC}} = \underbrace{\frac{\partial w_H/w_L}{\partial h_H/h_L} \frac{\partial h_H/h_L}{\partial \tau_g}}_{\text{HC}_g(1)} + \underbrace{\frac{\partial w_H/w_L}{\partial \tilde{A}} \frac{\partial \tilde{A}}{\partial h_H} \frac{\partial h_H}{\partial \tau_g}}_{\text{HC}_g(2)}.$$

We find that an increase in taxes (labor or robot) always increases the human capital ratio, h_H/h_L . This result is driven by the assumption of a hierarchical education system. Indeed, while an increase in the spending for basic education benefits the human capital of both types of workers, an increase in spending in higher education only benefits the human capital of high-skilled workers. Therefore, as $\phi_B \in (0, 1)$, an increase in aggregate education spending financed by increased taxation leads to an increase in both basic and college education spending, which benefits mostly the high-skilled

¹⁷This is without loss of generality as the effects via transfers are already captured within the redistribution channel; compare the previous footnote.

workers. This implies that $HC_g(1)$ is always positive. Also the second term, $HC_g(2)$, is always positive as increased human capital of high-skilled workers – via the R&D process (10) – leads to higher machine intensity, \tilde{A} , and thus – via their complementarity in production (6) – to higher wages of high-skilled workers. This implies that higher taxes (labor or robot) unambiguously increase the wage ratio w_H/w_L and hence consumption inequality through the human capital channel. The following proposition summarizes these findings.

Proposition 3.2. *An increase in taxation via the linear labor tax τ_W or the ad-valorem robot tax τ_R unambiguously increases consumption inequality, c_H/c_L , through the human capital channel.*

Since the redistribution channel reduces consumption inequality in the empirically relevant situation in which low-skilled workers receive proportionally more transfers, while the human capital channel always increases consumption inequality, the overall effect of taxation is ambiguous. We therefore proceed with a quantitative exercise for a calibrated environment to determine the net effect of a change in tax policy on inequality. In order to simultaneously analyze the effect on production growth, we also take into account the endogenous household response in terms of educational choices (extensive margin) and individual labor supply (intensive margin). That is, we allow for adjustments in the ability threshold a^* and calibrate $\gamma > 0$. Although these general equilibrium adjustments modify the precise nature of the redistribution and the human capital channels, their sign is preserved.

4 Calibration and model dynamics

4.1 Calibration

We calibrate our model to the US economy; a model period corresponds to 25 years. Ten parameters are externally calibrated. We set $\beta = 0.55$, which corresponds to an annual risk-free interest rate of about two percent. The parameter $\gamma = 1.242$ is set such that we can match the average US gross saving rate of 0.197 from 1971-2020 (FBEA, US Bureau of Economic Analysis, 2022). The elasticity of output with respect to effective human labor that can easily be automated is set in line with Prettnner and Strulik (2020) who propose a value of $\alpha = 0.80$. Innate learning abilities are assumed to be normally distributed with a mean of 100 and standard deviation $\sigma = 15$, with which we try to mimic the empirically observed IQ distribution. We assume that, in the limit, only half of the population can obtain a college education; this implies $\underline{a} = 100$.¹⁸ The fixed time fraction high-skilled workers need to spend in higher education is set at $\eta = 0.11$. We arrive at this value by assuming that individuals have a working-age period of approximately 44 years between leaving high school (at age 19) and retiring (at age 63), and that the time spent in higher education

¹⁸Prettnner and Strulik (2020) use the same strategy for the parameter \underline{a} .

amounts to five years. The size of one generation is normalized to $N = 1000$. The intertemporal knowledge spillover parameter $\lambda_1 = 0.335$ and the congestion externality parameter $\lambda_2 = 0.606$ are set in line with [McMorrow and Röger \(2009\)](#). The interest rate factor $\bar{R} = 1.6032$ is set to match the average effective federal funds rate from 1998-2022 of 1.906 percent ([Board of Governors of the Federal Reserve System \(US\), 2022](#)).

The remaining eight parameters are internally calibrated via a simulated method of moments (SMM). The initial technology level A_0 , the R&D productivity parameter δ , the disutility parameters for educational effort ψ_1 and ψ_2 and the parameters governing the effectiveness of the education system (μ_B , μ_H , B and B_H) are set to fit the following eight targets: a human capital level of the high-skilled individuals of one in the most recent model period (normalization); a share of college graduates of 37.9 percent in the year 2021 ([US Census Bureau, 2022](#)); a college wage premium – calculated as the ratio of the median income of individuals with tertiary education relative to the median income of individuals with upper secondary and post-secondary non-tertiary education – of 1.9 in 2021 ([Eurostat, 2022](#)); an average annual TFP growth rate of approximately 0.842 percent ([OECD, 2022a](#)); an average employment share in the R&D sector of around 1.1 percent ([NSF, 2017](#)); an average elasticity of low-skilled wages with respect to per-capita spending on basic education of 0.7 ([Jackson et al., 2015](#)); an average R&D spending share of around 2.69 percent ([World Bank, 2018](#)) and an average elasticity of college attendance with respect to its price of 1.5 ([Dynarski, 2003](#)).

Finally, the baseline configuration of fiscal policy $\{\tau_W, \tau_R, \phi, \phi_B, \omega\}$ is set as follows. The average labor income tax rate ($\tau_W = 0.2840$) is taken from [OECD \(2022d\)](#) and the average robot tax ($\tau_R = 0.05$) is set in line with [Acemoglu et al. \(2020b\)](#). The share of government spending on education that is used for higher (college) education amounts to 0.91 percent of GDP in the US for the year 2017, whereas the share that is spent on basic (primary and secondary) education is 3.24 percent for the same year ([OECD, 2022b](#)). Therefore, total government spending on education amounts to 4.15 percent of GDP, with a share of basic education spending within total government spending on education of $\phi_B = 0.7814$. We observe in the data that total social spending relative to GDP net of public pension payments makes up a share of 11.3 percent in 2017 ([OECD, 2022c](#)).¹⁹ Summing up both parts of the government budget and calculating the share of government spending on education within total government spending then leads to $\phi = 0.2673$. The share of total lump-sum transfer payments to low-skilled individuals ω_t is specified as time-varying and set such that the implied progressivity of the model’s tax and transfer system is constant over time and in line with $\rho(\omega_t) = \rho^{US} = 0.181$, which is the value estimated for the US by [Heathcote et al. \(2017\)](#).²⁰

¹⁹We reduce total social spending by pension payments as our model abstracts from pension payments when households reach the retirement age.

²⁰In detail, we calculate the discrete elasticity of post-government ($\tilde{y}_{i,t}$) to pre-government ($y_{i,t}$) earnings; this elasticity is then evaluated at the low-skilled income level, with ω_t adjusting such that the following condition is

External parameters		
β	0.55	discount factor
γ	1.242	Frisch elasticity
α	0.80	elasticity of output with respect to effective human labor
σ	15	std. dev. ability
\underline{a}	100	mean ability
η	0.11	time spent in tertiary education
N	1.000	population size
λ_1	0.335	intertemporal knowledge spillover
λ_2	0.606	congestion externality
\bar{R}	1.6032	interest rate
Internal parameters		
A_0	27	initial technology level
δ	0.55	R&D productivity parameter
ψ_1	0.37	educational effort parameter
ψ_2	21.93	educational effort parameter
μ_B	0.28	effectiveness of per capita government spending on basic education
μ_H	0.13	effectiveness of per capita government spending on higher education
B	1.47	basic education productivity parameter
B_H	3.38	higher education productivity parameter
Baseline policy		
τ_W	0.284	linear income tax rate
τ_R	0.050	robot tax rate
ϕ	0.267	share of total government spending to education spending
ϕ_B	0.781	share of government education spending to basic education spending
ω_t	Fig. (1)	share of lump-sum transfers to low-skilled workers

Table (1) Calibration parameters; more details, see text.

The parameters used for the initial calibration are summarized in Table (1). In addition, Table (2) reports the fit of the calibrated baseline model to the relevant moments in the data.

4.2 Model dynamics

Figure (1) shows the model dynamics for the calibrated economy, which displays endogenous growth and endogenous skill acquisition under the baseline fiscal policy $\{\tau_W, \tau_R, \phi, \phi_B, \omega_t\}$. We observe fulfilled in each period,

$$\frac{\Delta \tilde{y}_{i,t}}{\Delta y_{i,t}} \frac{y_{i,t}}{\tilde{y}_{i,t}} = \frac{(1 - \tau_W)[w_{H,t}\tilde{h}_t - w_{L,t}\tilde{l}_t] + [\hat{T}_{H,t} - \hat{T}_{L,t}]}{[w_{H,t}\tilde{h}_t - w_{L,t}\tilde{l}_t]} \frac{w_{L,t}\tilde{l}_t}{(1 - \tau_W)w_{L,t}\tilde{l}_t + \hat{T}_{L,t}} = 1 - \rho^{US} = 0.819,$$

where $\hat{T}_{L,t} = \frac{\omega_t T_t}{L_t}$, $\hat{T}_{H,t} = \frac{(1 - \omega_t)T_t}{H_t}$, and where \tilde{h}_t and \tilde{l}_t denote the effective labor supply of a high-skilled and low-skilled individual, respectively.

Target	Data	Model
high-skilled human capital (normalization)	1.0000	1.0000
college share	0.3790	0.3790
R&D expenditure share	0.0269	0.0197
R&D employment share	0.0110	0.0136
wage premium	1.9000	1.9213
elasticity of college attendance wrt. its price	1.5000	1.3976
elasticity of low-skilled wages wrt. per-capita spending on lower education	0.7000	0.4873
TFP growth	0.8420	0.8420

Table (2) Goodness of fit of the baseline model.

that the R&D induced productivity growth of machines leads to an exponential increase in TFP, production and automation (i.e., the use of machines in the final production sector) over time. Given workers' different degrees of complementarity with machines, this increased productivity of machines disproportionately benefits the high-skilled workers, exponentially increasing the *skill premium* measured via the pre-tax ratio of high- to low-skilled wages, w_H/w_L . The corresponding consumption ratio c_H/c_L (which is equal to the after-tax and transfer income ratio) follows a similar pattern, even though the tax-and-transfer system in place is progressive at $\rho = 0.181$. Throughout, post-government income inequality is slightly below its pre-government value as transfers are used to redistribute resources from high- to low-skilled individuals. But quantitatively wage inequality provides a good approximation for consumption and income inequality.

As seen, there is actually a decline in ω_t , the share of lump-sum transfers to low-skilled workers.²¹ Importantly, this is consistent with constant progressivity in the fiscal system as the share of low-skilled individuals is declining. This is because the increased skill premium creates stronger incentives to undertake education so that the threshold value a^* falls, implying an increase in the total number of high-skilled workers.²² Given the constant population size N , there are thus fewer low-skilled workers whose per-capita transfers can be financed out of a lower transfer share ω_t .

The number of high-skilled workers employed in the final production sector monotonically increases, while the number of researchers (workers employed in the R&D sector) initially increases and then declines. The steep increase in the number of researchers in earlier years is due to the relatively low level of machine productivity which implies a high incentive to allocate high-skilled workers to the R&D sector to improve the productivity of the machines. However, as the productivity of machines becomes sufficiently high, the incentives reverse. This trend leads to a reduction in the number of researchers and to a sustained increase in the number of high-skilled workers employed in the final production sector.

²¹This reflects our calibration strategy, which lets ω_t adjust over time to keep progressivity constant, $\rho(\omega_t) = \rho$.

²²In the long-run, the educational threshold converges, $a^* \rightarrow \underline{a}$.

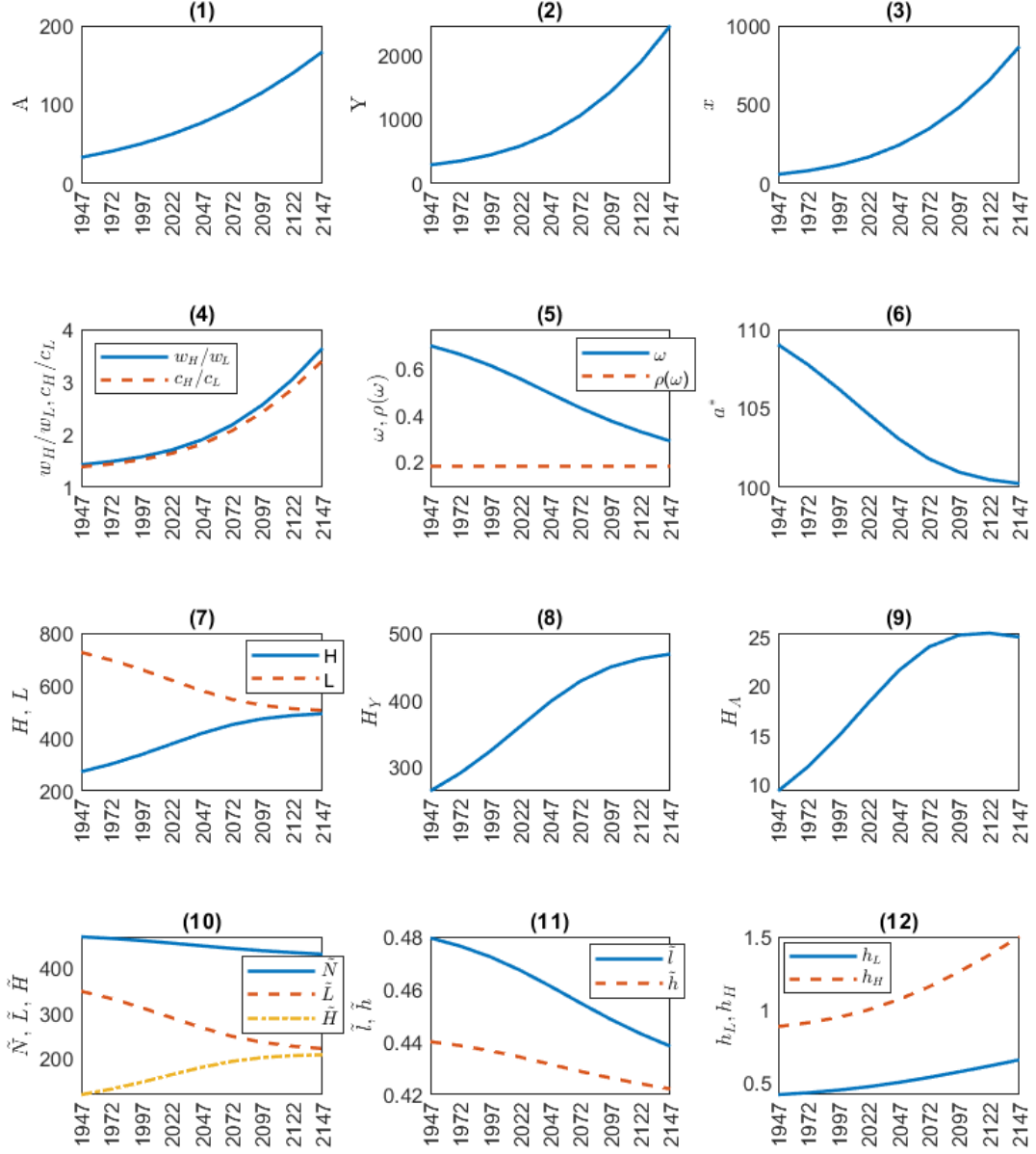


Figure (1) Model dynamics for the initial calibration to the US economy.

These changes along the extensive margin are accompanied also by movements along the intensive margin. Therefore, R&D induced automation does not only affect the composition of the labor force, but also the aggregate labor supply \tilde{N} . Indeed, while the individual labor supply of high-skilled workers \tilde{h} tends to decrease slightly over time, the individual labor supply of low-skilled workers \tilde{l} decreases more significantly due to the higher importance of per-capita transfers (transfers increase as the economy grows).²³ Although the individual labor supply of high-skilled workers slightly declines, aggregate high-skilled labor supply \tilde{H} rises, driven by the higher number of high-skilled individuals over time. The opposite is true for the aggregate labor supply of low-skilled individuals, \tilde{L} , owing to a decline in both individual labor supply and the number of low-skilled workers in the economy. Summing the effects across the two skill groups, we observe a mild contraction in aggregate labor supply because the negative effect on aggregate low-skilled labor supply dominates the positive effect on aggregate high-skilled labor supply.

Finally, human capital increases over time for both low- and high-skilled individuals. Indeed, under the baseline fiscal policy education spending is a constant fraction of GDP, and as production expands over time, both the spending on basic and higher education increase, leading to stronger human capital accumulation. The human capital ratio h_H/h_L increases also over time, which is in line with the argument from the partial equilibrium analysis where we have shown that, under a hierarchical education system, higher education spending creates higher inequality as it disproportionately benefits high-skilled individuals. There is thus a fundamental tension in that R&D driven productivity growth tends to accentuate inequality.

5 Exogenous policy analysis

In view of the above trade-off, we proceed by examining the implications of different fiscal policies for growth and inequality. We initially analyze the effect of changing fiscal policy along a *single dimension*, either on the financing side (i.e., the tax parameters τ_W and τ_R) or on the spending side (i.e., the education and transfer parameters ϕ , ϕ_B , ω). In a next step, we then consider also *mixed policies* where fiscal policy is altered along multiple dimensions. In all exercises, the policy parameter(s) in question is/are permanently altered in the base period (year 2022), and we track the subsequent dynamics in growth and inequality for the following period (year 2047).

Starting from the calibrated baseline configuration $\{\tau_W, \tau_R, \phi, \phi_B, \omega_t\}$ for fiscal policy, we find that no single dimension policy can reduce inequality without harming growth. The reason is that none of the policy instruments entails both growth-enhancing and inequality-reducing characteristics. By contrast, when considering mixed policies, there is a set of possible policy reforms that can both increase economic growth and reduce inequality. Here, we can combine policy instru-

²³Individual labor supply of high-skilled and low-skilled individuals is calculated from (4) as $\tilde{h}_t = 1 - \eta - z_{H,t}$ and $\tilde{l}_t = 1 - z_{L,t}$, respectively.

ments that on the one hand lead to lower growth and higher inequality with policy instruments that on the other hand work as a production booster and inequality reducer at the same time. If the positive effect on production of the first policy instrument dominates the negative effect of the second policy instrument and vice versa for the inequality dimension, a combined adjustment creates higher production and lower inequality compared to the initial situation.

5.1 Single policies

We first consider the effect of fiscal policy adjustments on growth and inequality in the year 2047 by changing one policy parameter only in the year 2022, while keeping the other parameters constant at their 2022 level. We start analyzing the effect of a change in the tax structure by modifying alternatively the labor tax (τ_W) or the robot tax (τ_R). We then analyze the effect of a change in the spending allocations by alternatively modifying the share of tax revenues that is allocated to education spending (ϕ) relative to transfers, the share of education spending that is allocated to basic education (ϕ_B) or the share of transfers that are redistributed to low-skilled workers (ω).

Tax policy Figure (2) shows that an increase in the labor tax and an increase in the robot tax actually have opposite effects on inequality. Considering an increase in the labor tax, the model predicts an increase in inequality measured either in terms of the consumption ratio c_H/c_L or the Gini coefficient,²⁴ and an increase in production growth. This implies that the human capital channel, which increases the wages of high- relative to low-skilled workers, is dominant relative to the redistribution channel. By contrast, when we consider an increase in the robot tax, inequality reduces as well as production growth. The robot tax is, indeed, more redistributive than the labor tax (cf. Proposition 3.1), and the redistribution channel dominates the human capital channel, leading to lower inequality.

Our results for the one-dimensional tax changes considered here are in line with [Prettner and Strulik \(2020\)](#), highlighting the trade-off between growth and equality, and that it is not possible to reduce inequality without harming economic growth through higher taxation alone. However, in contrast to their framework where an increase in either the labor or the robot tax unambiguously leads to lower inequality and lower growth, in our framework, the presence of endogenous human capital gives rise to differential effects of taxation: Increasing the more redistributive robot tax induces the familiar reduction in growth and inequality. But for the less redistributive labor tax, the fact that the tax revenue is spent in part on education implies that growth and inequality now augment growth and inequality.

²⁴While the consumption ratio does not take into account the endogenous change in the share of high- relative to low-skilled workers following the policy change, the Gini coefficient takes both the intensive margin (change in the ratio of individual consumption) and the extensive margin (change in the number of high- relative to low-skilled workers) into account. Qualitatively, results are generally robust across the two different inequality measures.

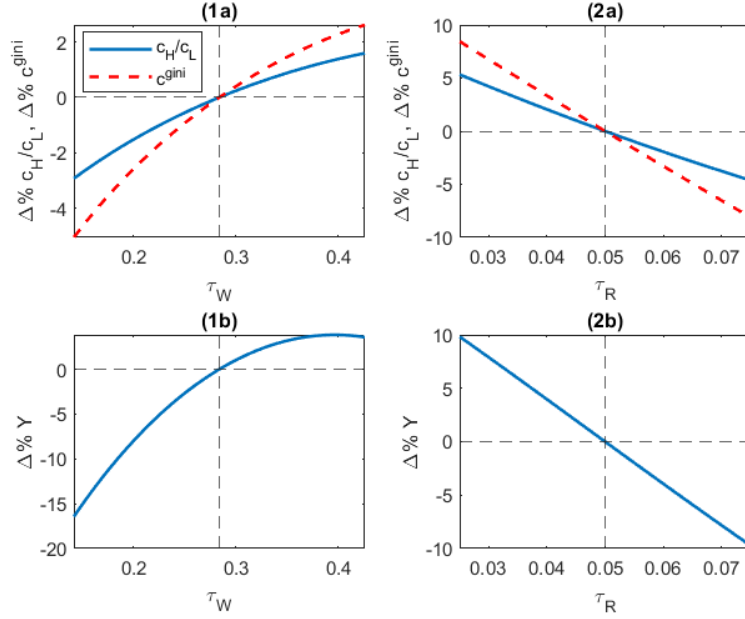


Figure (2) Fiscal policy analysis: effect of a change in labor tax (first column) and robot tax (second column) on inequality (first row) and production (second row) for the year 2047 in percentage deviations from the initial calibration.

Education and transfer policy Turning to changes in the allocation of public spending, Figure (3) shows the effects on production growth and inequality of a change in (i) ϕ , the education share of public spending; (ii) ϕ_B , the share of education spending allocated to basic education; and (iii) ω , the share of transfers that is given to low-skilled workers. We observe that an increase in ϕ increases both inequality (through the human capital channel) and economic growth as it increases the incentives to acquire higher education. An opposite result is obtained if we consider an increase in ϕ_B ; this is because, given a fixed overall budget share ϕ for education, an increase in the share ϕ_B devoted to basic education corresponds to a reduction in spending in higher education, which disincentivizes enrollment in higher education and reduces production growth. Finally, given the total budget share $1 - \phi$ available for transfers payments, an increase in the share ω of transfers given to low-skilled workers reduces inequality and production growth due to the lower incentives to engage in education and R&D.

5.2 Mixed policies

So far, we have shown that higher growth and lower inequality cannot be reached when considering single policies alone. Now, we present a series of mixed policy experiments in which we allow joint changes of two policy parameters. Starting from the baseline US tax structure in place in 2022, we show that a coordinated joint adjustment of τ_W and τ_R can lead to both an increase in economic growth and a reduction in inequality. We obtain similar results for other policy packages combining

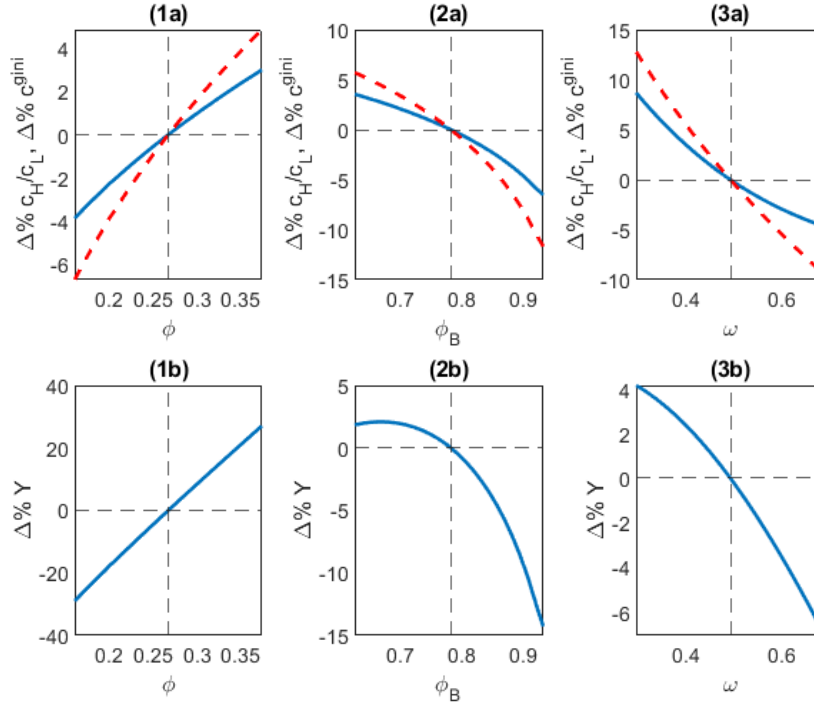


Figure (3) Fiscal policy analysis: effect of a change in labor tax (first column) and robot tax (second column) on inequality (first row) and production (second row) for the year 2047 in percentage deviations from the initial calibration.

a change in tax (τ_W or τ_R) or education policies (ϕ or ϕ_B) with redistribution policies (i.e., a change in the degree of progressivity, ω). The basic idea is to use one policy instrument to boost growth (i.e., a reduction in τ_R or an increase in τ_W , ϕ or ϕ_B) and the other instrument to compensate the low-skilled workers suffering from the growth-enhancing policy (i.e., an increase in ω). Throughout, the balanced-budget assumption is maintained.

Change in the tax structure Figure (4) shows the combined effect on production and inequality of a change in both the labor and the robot tax. We can distinguish four color-coded regions: green indicates tax combinations resulting in higher production and lower inequality relative to the status quo; red indicates combinations resulting in lower production and higher inequality; yellow and orange, respectively, indicate tax profiles leading to higher production and inequality (yellow) or lower production and inequality (orange).²⁵

We observe that an increase in the robot tax combined with an increase in the labor tax can lead

²⁵Notice that the color coding in Figure (4) and (5) condenses the induced macroeconomic outcomes into a simple directional indicator (higher/lower relative to the initial situation) and is silent about the intensity of the relevant effects. The Figures can therefore not be readily used for welfare analysis. First, we need to define a welfare metric that accounts for both, the effects of changes in production and inequality, on high- and low-skilled individuals. The welfare analysis can be found in Section 6.

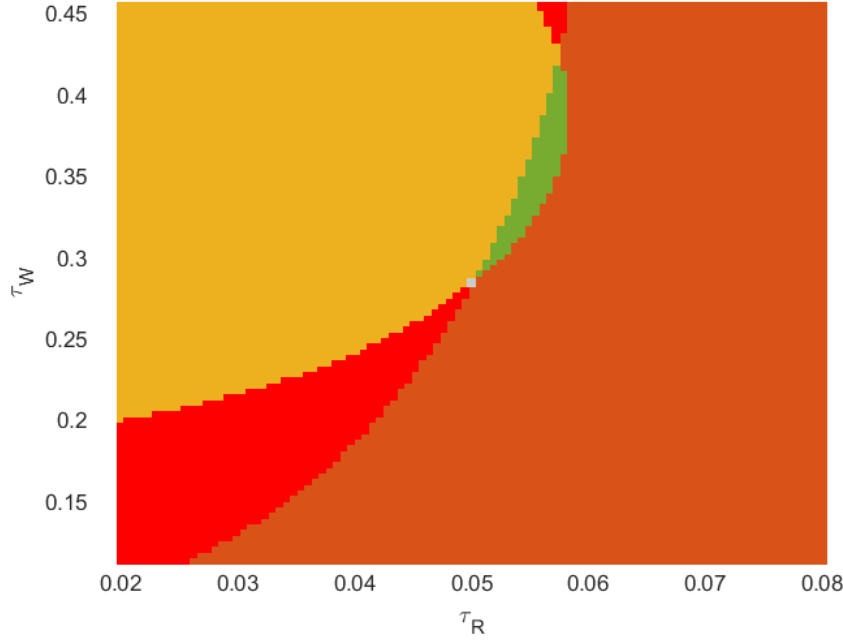


Figure (4) Two-dimension policies on the tax structure; in grey: initial situation calibrated to the US economy; in green: good no-trade-off region (higher production, lower inequality); in red: bad no-trade-off region (lower production, higher inequality); in yellow: trade-off region 1 (higher production, higher inequality); in orange: trade-off region 2 (lower growth, lower inequality).

to both higher production and lower inequality. Recall from Figure (2) that a higher labor tax boosts production growth by increasing the human capital of both low- and high-skilled workers. However, since the higher education spending financed by the higher labor tax disproportionately benefits the high-skilled workers, the increase in the labor tax also increases inequality. The increase in the robot tax, instead, has the opposite effect. Indeed, since it directly reduces the labor productivity of high-skilled workers, an increase in the robot tax reduces both production and inequality. The green region in Figure (4) identifies combinations of the two tax instruments such that the increase in production driven by the increase in the labor tax is stronger than the reduction driven by the increase in the robot tax, and the reduction in inequality driven by the robot tax is stronger than the increase driven by the labor tax.²⁶

Change in tax or education policy accompanied by transfer policy Figure (5) considers the combined effect on production and inequality of a change in tax or education policy accompanied by a change in the share of transfers going to low-skilled workers (ω). Panel one shows that, in order to reach the green region in which higher production is compatible with lower inequality, both labor taxes and the degree of redistribution towards low-skilled workers need to increase. On

²⁶The results with respect to inequality are based on the consumption ratio as the relevant measure for inequality. Results are qualitatively similar when using the Gini coefficient as the relevant measure for inequality.

the one hand, the higher labor taxes finance education spending that increases the human capital and the productivity of both skill types. On the other hand, to offset the increased inequality from higher labor taxes (the higher education spending benefits relatively more the high-skilled, see Figure (2)), higher redistribution towards low-skilled workers is necessary, calling for an increase in ω . In the green region, therefore, the increase in production induced by the increase in the labor taxes is sufficiently pronounced to compensate the low-skilled workers via increased transfers.

In panel two, we observe that the green region can be reached by reducing the robot tax while simultaneously increasing redistribution towards low-skilled workers. Different from the labor tax, the robot tax directly reduces high-skilled productivity since it discourages the adoption of machines, which reduces production growth. A reduction in machine adoption also positively affects low-skilled workers which are substitutes for machines. Therefore, in order to both enhance production and reduce inequality, a reduction in the robot tax needs to be coupled with an increase in the share of transfers toward low-skilled workers. Indeed, the reduction in the robot tax increases the incentives for machine adoption and thus boosts growth. This allows the government to fund additional transfer payments compensating the low-skilled workers for the wage compression due to the higher competition coming from machines.

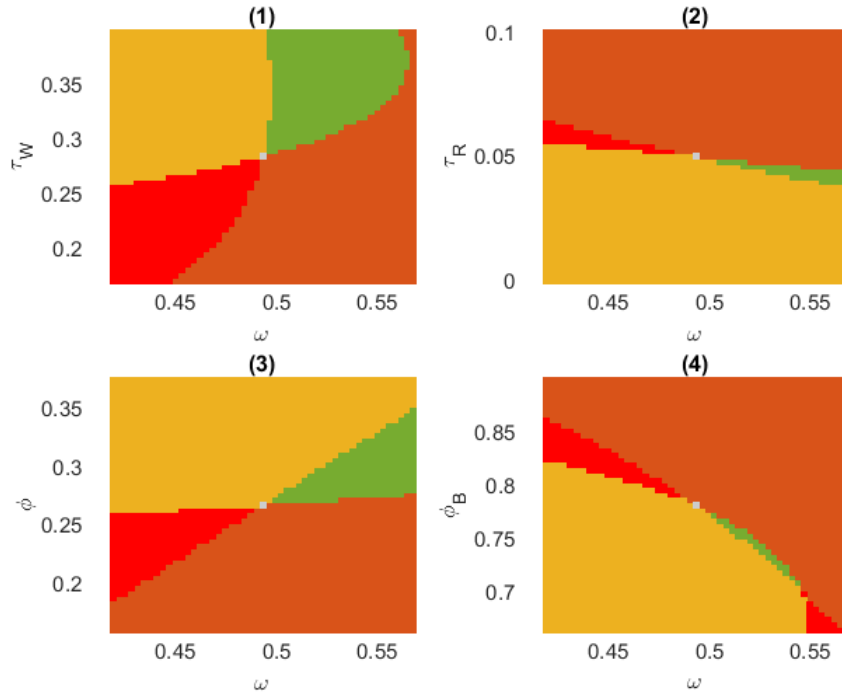


Figure (5) Two-dimension policies on either the tax rates or education variables in combination with transfer policy; in grey: initial situation calibrated to the US economy; in green: good no-trade-off region (higher production, lower inequality); in red: bad no-trade-off region (lower production, higher inequality); in yellow: trade-off region 1 (higher production, higher inequality); in orange: trade-off region 2 (lower growth, lower inequality).

Panels three and four Figure (5) examine similar reforms, which now involve the generosity and composition of education spending. In panel three, we observe that an increase in the budget share of total education spending (ϕ) can both boost production and reduce inequality if this policy is coupled with an increase in the share of transfers towards low-skilled workers (ω). On the one hand, the increase in the share of total education spending increases production growth by augmenting the human capital of both low- and high-skilled workers; on the other hand, the increased transfers to low-skilled workers can compensate for the fact that the higher education spending is financed by a reduction in total transfers, which tends to increase inequality. Therefore, to obtain higher production and lower inequality, total transfers should be reduced to finance education spending and should be directed more towards low-skilled workers.

Finally, panel four shows that to reach the green region, the share of education spending going to basic education must reduce (i.e., the share of higher education spending must increase), while the share of transfers to low-skilled workers needs to increase. On one side, the higher share of education spending on college education increases production growth since the human capital gains for high-skilled workers are large enough to compensate for the reduced human capital formation for low-skilled workers. On the other side, compensating transfer payments to reduce inequality should then be directed more towards low-skilled workers.

6 Optimal tax schedule

In the previous section, we find several combinations of policies leading to both higher production growth and lower inequality, thereby breaking the equity-growth trade-off. However, since the initial condition is not welfare maximizing, the welfare-maximizing policy combination does not necessarily need to lie in the green area.²⁷ Indeed, the welfare-maximizing policy can lie in either the green, the yellow, or the orange region (i.e., anywhere but the red region in which both economic growth is lower and inequality is higher) depending on the weights given to high- and low-skilled utilities in an aggregate welfare function.

In this section, therefore, we estimate the optimal tax schedule and examine how it changes depending on the weight the planner attaches to low-skilled workers, and analyze how it evolves over time. We define the optimal tax schedule as the combination of labor tax and robot tax that maximizes social welfare defined as a combination of the lifetime utility of low-skilled and high-skilled individuals:

²⁷In the case in which the initial condition was already the welfare maximizing one, no green region would emerge because any increase in growth without any increase in inequality (or a reduction in inequality without any reduction in growth) would lead to higher welfare contradicting the initial assumption that the starting point was the welfare maximizing.

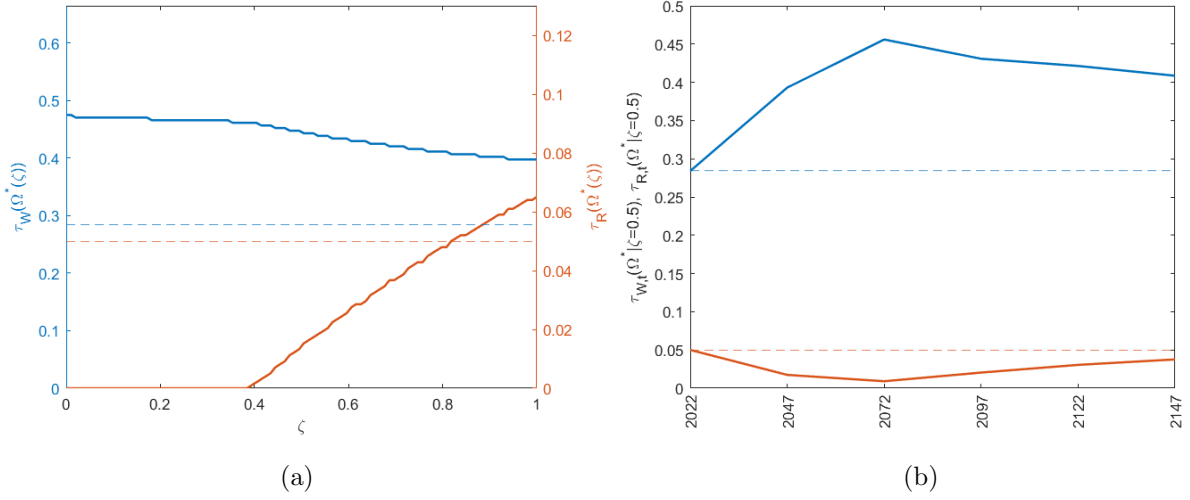


Figure (6) Panel (a) shows the optimal tax schedule (combination of labor and robot tax) for the first period after the initial period (year 2047) dependent on the welfare weight ζ . Panel (b) shows the optimal dynamic tax schedule (for a given welfare weight of $\zeta = 0.5$). The broken lines in both panels represent the initially calibrated situation for the labor income tax (blue) and the robot tax (orange) in which both tax rates are assumed to be constant.

$$\Omega_t = \zeta \cdot \underbrace{F(a_t^*) \cdot N \cdot \mathcal{U}_{L,t}}_{=L_t} + (1 - \zeta) \cdot \underbrace{(1 - F(a_t^*)) \cdot N \cdot \mathcal{U}_{H,t}}_{=H_t}, \quad (14)$$

where ζ is the weight that the social planner places on the welfare of the low-skilled workers measuring the preference of the social planner for equality rather than production growth.²⁸

Figure (6), panel (a) shows that the welfare optimal tax schedule for 2047 varies depending on ζ . In particular, for very low levels of ζ , corresponding to a small weight given to low-skilled workers (or, equivalently, a small preference for equity), the optimal robot tax is zero, while for higher levels of ζ , the optimal robot tax turns positive and increases as the weight given to equity increases. The robot tax, indeed, mostly affects high-skilled workers directly reducing the incentives to adopt machines. The labor tax is, instead, declining in ζ as the labor tax mostly benefits high-skilled workers through the human capital channel. Independent of the value of ζ , welfare optimality requires an increase of the linear labor income tax rate relative to the initial situation, driven by the fact that an increase in this tax rate creates positive growth effects on production. In addition, for values of ζ smaller than around 0.8, welfare optimality requires a decline in the robot tax relative to the initial situation. For very high values of ζ (larger than around 0.8), the robot tax should optimally increase compared to the initial situation, driven by the fact that redistributive concerns

²⁸We focus on the optimal tax schedule because we are interested in the interaction of the two instruments that behave in the exact opposite way with respect to production growth and inequality and are therefore able to break the equity-growth trade-off. In addition, we are not interested in adjusting progressivity of the tax-and-transfer system and want to keep the allocation of government spending constant.

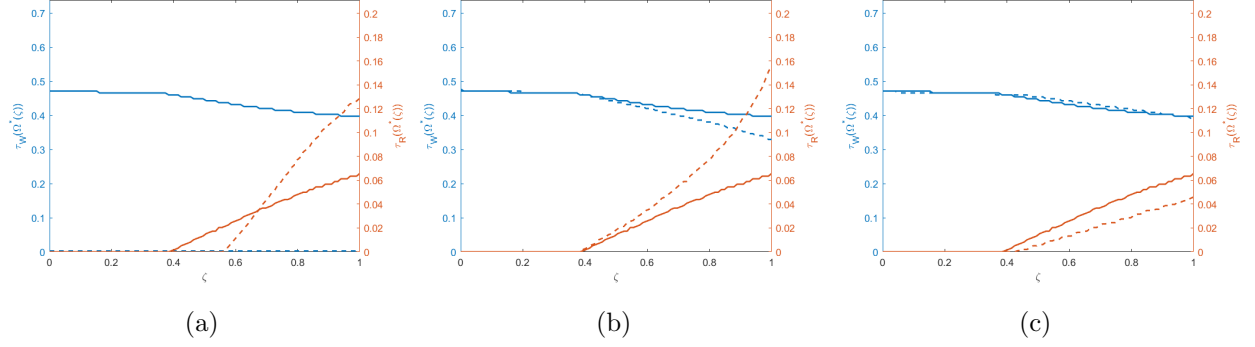


Figure (7) Optimal tax schedule (combination of labor and robot tax) for the first period after the initial period (year 2047) dependent on the welfare weight ζ . Solid lines in all panels are results for the full adjustment scenario. Broken lines in Panel (a) are results for the effect of the extensive margin in which human capital is fixed at its initial level. Panel (b) shows results for the effect of the intensive margin in which the number of skill types is kept at its initial level. Progressivity of the tax-and-transfer system is fixed at its baseline level for panels (a) and (b). Panel (c) shows results on keeping ω fixed at its initial level and progressivity of the tax-and-transfer system adjusts.

are stronger weighted in the aggregate welfare function with higher ζ values.

Figure (6), panel (b) instead shows the optimal dynamic tax schedule fixing $\zeta = 0.5$. Relative to the initial calibration, the planner should initially reduce the robot tax to a significantly lower level making use of the increase in revenues with the higher labor tax. Then the government should progressively increase the robot tax and reduce the labor tax over time. An initial lower robot tax, indeed, creates incentives to invest in R&D enhancing machine productivity which is the driver of economic growth. As machine productivity increases and the wage gap widens, the government finds it optimal to reduce inequality. Since the robot tax is a redistributive tax and the labor tax benefits mostly the high-skilled workers, the government optimally increases the robot tax and reduces the labor tax over time. This result crucially depends on the introduction of endogenous human capital. In a model with exogenous human capital as in [Prettner and Strulik \(2020\)](#), indeed, we observe that, although the government might find it optimal to impose a labor tax in order to transfer resources to low-skilled workers, the robot tax is optimally zero or very close to zero since, relative to the labor tax, the robot tax has a stronger negative effect on economic growth.²⁹ In our model with endogenous human capital, instead, after the initial period, the optimal robot tax becomes significantly positive and higher relative to the model with exogenous human capital. Endogenous human capital, indeed, renders the robot tax less harmful to growth because education provides a further reason to optimally set a positive robot tax.

Figure (7) provides a decomposition of the relevant role in shaping the pattern of optimal taxes of adjustments in the supply of skills along the intensive and the extensive margin as well as in the

²⁹In the [Prettner and Strulik \(2020\)](#) model with exogenous human capital, the optimal robot tax might not be equal to zero since automation is a perfect substitute to low-skilled labor and an increase in the robot tax does not directly harm the productivity of low-skilled workers and it can have welfare-enhancing effects.

overall progressivity of fiscal policy. Panel (a) shows the effect of the extensive margin on optimal tax rates. Human capital for both skill types is fixed at its initial level and all other variables adjust as in the baseline scenario. Not considering the human capital effect of tax policies leads to a completely different result regarding the optimality of the linear income tax rate. The optimal linear income tax rate immediately drops down to virtually zero as all positive effects that are created for production are neglected while keeping the human capital of both skill types at their initial level. In addition, if the government puts more weight on the low-skilled individuals in the economy, optimality requires an even higher robot tax. Panel (b) shows the consequences of the intensive margin on optimal tax rates, keeping the number of high- and low-skilled individuals at their initial level and letting all other variables adjust. Results do not change dramatically. For both experiments, progressivity of the tax-and-transfer system stayed untouched such that ω adjusted to keep progressivity constant at its initial level. Panel (c) shows results for keeping the time path of ω at its initial level and letting progressivity of the tax-and-transfer system adjust. Results hardly change. The robot tax optimally reduces for higher levels of ζ because progressivity endogenously increases, leading to less necessity for redistribution through the robot tax.

7 Private college education spending

In countries such as the United States, private spending for a college education is an important fraction of total college education spending. Public education spending can affect the private education spending decision of the agents as those types of spending substitute one another. To take this channel into account, we augment our model with endogenous private college education spending. The budget constraint of an individual of type $j = \{L, H\}$ then becomes:

$$(1 - \tau_W)(1 - \eta_j - z_{j,t})w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]} \theta_t = c_{j,t} + s_{j,t}, \quad (15)$$

where θ_t represents private spending in higher education. The variable θ_t is a choice variable of the agent and by assumption zero if the agent does not acquire higher education ($j = L$), but pinned down by the following first-order condition in the case in which the agent goes to college ($j = H$):

$$1 = (1 - \tau_W)(1 - \eta - z_{H,t}) \frac{\partial w_{H,t}}{\partial \theta_t}, \quad (16)$$

where we have assumed that private college education spending affects the human capital of high-skilled workers and, therefore, their wages. In particular, private education spending in higher education is an imperfect substitute to public education spending in higher education and it affects the human capital of high-skilled workers according to:

$$h_{H,t} = B_H \cdot (h_{B,t})^{1-\mu_H} \cdot \left(\epsilon^{\frac{1}{\nu}} (\theta_t)^{\frac{\nu-1}{\nu}} + (1 - \epsilon)^{\frac{1}{\nu}} \left(\hat{E}_{H,t} \right)^{\frac{\nu-1}{\nu}} \right)^{\frac{\nu}{\nu-1} \mu_H}, \quad (17)$$

where $\nu \in (0, \infty)$ governs the elasticity of substitution between private and public education spending on higher education and $\epsilon \in (0, 1)$ is the share parameter of this constant elasticity of substitution aggregate.³⁰ This implies, that:

$$\frac{\partial w_{H,t}}{\partial \theta_t} = (1 - \alpha)^2 \frac{\left((h_{L,t} \tilde{L}_t)^\alpha + \tilde{A}_t x_t^\alpha \right)}{(h_{H,t} \tilde{H}_{Y,t})^\alpha} \cdot \frac{\partial h_{H,t}}{\partial \theta_t},$$

$$\frac{\partial h_{H,t}}{\partial \theta_t} = B_H h_{B,t}^{1-\mu_H} \mu_H \left[\epsilon^{\frac{1}{\nu}} (\theta_t)^{\frac{\nu-1}{\nu}} + (1 - \epsilon)^{\frac{1}{\nu}} \left(\hat{E}_{H,t} \right)^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1} \mu_H - 1} \epsilon^{\frac{1}{\nu}} \theta_t^{-\frac{1}{\nu}}.$$

Exogenous fiscal policy Including private college education spending has qualitative implications on the effects of fiscal policies. In particular, while the effects on growth and inequality are similar when considering changes in the robot tax, τ_R , or in the share of transfers to low-skilled workers, ω , results are qualitatively different when considering a change in the labor tax, τ_W , education spending, ϕ , or basic education spending ϕ_B . Indeed, in the model with private college education spending, an increase in the labor tax reduces both inequality and production growth (column 1, Figure (8)).

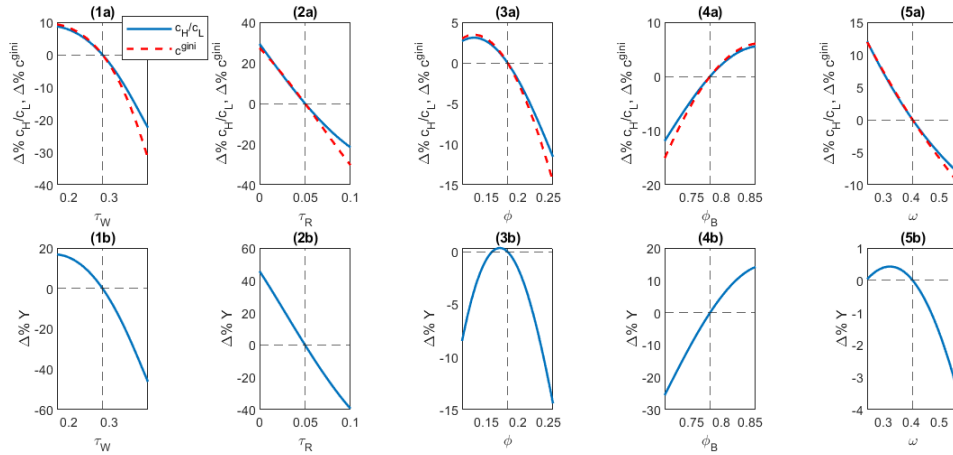


Figure (8) Fiscal policy analysis including private spending: effect of a change in the labor tax (first column), the robot tax (second column), the spending share on education (third column), the spending share on basic education (fourth column) and the share of transfer payments to low-skilled individuals (fifth column) on inequality (first row) and production (second row) in percentage deviations from the initial calibration.

Since private and public college education spending are substitutes, an increase in the labor tax and, therefore, an increase in public college education spending, crowds out private college education spending. This reduces the effect going through the human capital channel which is then dominated by the redistribution channel leading to a reduction in inequality. Similarly, this happens

³⁰Equation (17) is equal to the high-skilled human capital in the case of no private spending on higher education in (2.5) in the case of $\epsilon = 0$ and $\nu \rightarrow \infty$.

as the share of education spending increases (column 3). Higher public education spending increases public college education spending which crowds out private college education spending leading to a reduction in the effect going through the human capital channel. Finally, as basic education spending increases, the effects on growth and inequality are opposite relative to the model without private education spending (column 4). An increase in public basic education spending increases the incentives to increase private spending in private college education spending as basic education and college education are complementary in the human capital production function of high-skilled workers. This increases the human capital of high-skilled workers more than the human capital of low-skilled workers leading to an increase in inequality and, through the higher incentive to acquire higher education, it increases production growth.

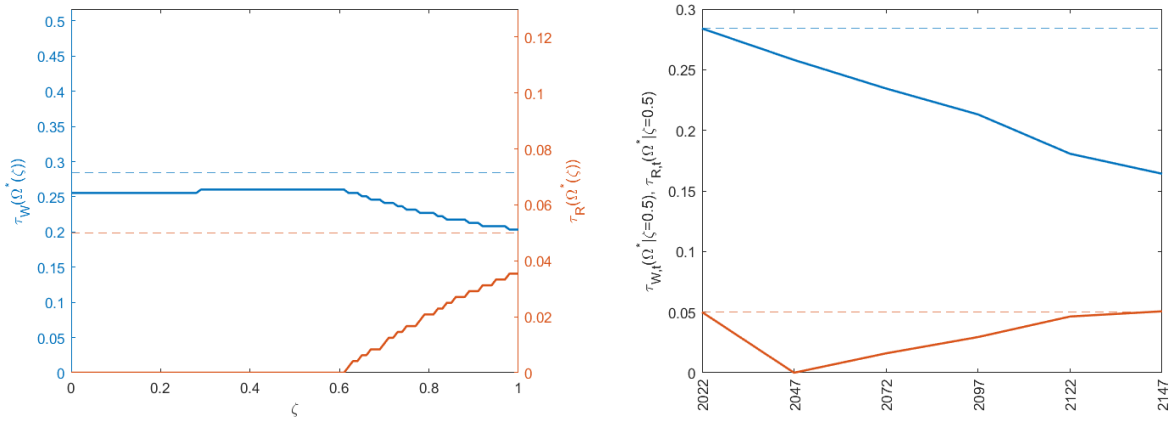


Figure (9) Graph (a) shows the optimal tax schedule (combination of labor and robot tax) dependent on the welfare weight ζ , when private education spending is included in the model structure. Graph (b) shows the optimal dynamic tax schedule ($\zeta = 0.5$), also taking private education spending into account.

As a final finding, we observe that the relationship between public education spending and production growth is non-monotonic, it is first increasing and then declining. This reflects the combination of two forces: for low levels of public education share (ϕ), an increase in the public education share leads to an increase in production growth driven by the increase in public basic education which stimulated higher private college education spending, however, for higher levels of public education share, the higher public college education spending crowd out private college education spending reducing inequality and production growth (3b). Using State-level data for the United States, we observe that the non-linear relation between education spending and GDP is consistent with the empirical evidence (Table (5)).

Optimal fiscal policy Figure (9) panel (a) shows the optimal tax schedule depending on different levels of ζ , the weight attached to low-skilled workers. As for the case with no private college education spending, the optimal robot tax is zero for low levels of ζ and it becomes positive and increases the higher the weight given to low-skilled workers. Differently from the case without

private spending in which the labor tax is monotonically declining, when including private education spending, the labor tax is initially increasing and then declining in ζ . The initial increasing part is due to the fact that the labor tax in the model with private spending reduces inequalities. Therefore, as the weight given to low-skilled workers increases, the optimal labor tax increases as well. This holds true as long as the optimal robot tax is equal to zero. For higher levels of ζ , the government finds it optimal to substitute the labor tax with the robot tax since it is more redistributive. Therefore, for higher levels of ζ , the labor tax declines, and the robot tax increases.

8 Targeted education spending - NOT COMPLETE

We allow the government to spend its higher education resources $E_{H,t}$ not only on colleges (increasing human capital of high-skilled individuals) but also on on-the-job training measures (directly increasing the human capital of low-skilled individuals), formally allowing $h_{L,t}$ to differ from $h_{B,t}$. On-the-job training measures require some (fixed) time investment of low-skilled workers ($\eta_L > 0$) into some sort of vocational training. But, we assume that time spent in on-the-job training measures can never exceed the time spent in college education ($\eta_L < \eta_H$). We neither allow high-skilled nor low-skilled individuals to privately invest in higher education. Therefore, the human capital of high-skilled individuals follows again the baseline modeling strategy and the human capital of low-skilled individuals follows a similar pattern as the human capital of high-skilled individuals (without private education investment):

$$h_{L,t} = B_L \cdot (h_{B,t})^{1-\mu_L} \cdot \left(\hat{E}_{HL,t} \right)^{\mu_L} \quad (18)$$

where $\hat{E}_{HH,t} \equiv \frac{E_{HH,t}}{H_t}$ ($\hat{E}_{HL,t} \equiv \frac{E_{HL,t}}{L_t}$) is the per capita government spending on higher education on high-skilled (low-skilled) individuals. The parameter $\mu_L \in (0, 1)$ governs the effectiveness of higher per capita government education spending on the human capital of low-skilled individuals. $B_L > 0$ is a type-specific productivity parameter. Total government spending on higher education $E_{H,t}$ is split up into higher education spending on high-skilled individuals $E_{HH,t}$ and higher education spending on low-skilled individuals $E_{HL,t}$:

$$E_{H,t} = E_{HH,t} + E_{HL,t}. \quad (19)$$

Higher education spending on high-skilled (low-skilled) individuals is a fraction $\phi_{HH} \in (0, 1)$ ($1 - \phi_{HH}$) of total government spending on higher education:

$$E_{HH,t} = \phi_{HH} \cdot E_{H,t}, \quad (20)$$

$$E_{HL,t} = (1 - \phi_{HH}) \cdot E_{H,t}. \quad (21)$$

9 Conclusion

In this paper, we highlight the importance of human capital channel through which education spending enhances production growth and affects inequality. We observe that while the robot tax has redistributive effects and reduces inequality at the cost of lower growth, the labor tax tends to benefit the high-skilled workers, increasing both inequality and production growth. Allowing for private college spending affects the results qualitatively. In this case, either an increase in the labor or the robot tax lead to lower inequality and lower growth since the higher education spending driven by the higher taxes crowds out private education spending. Private college education spending, however, does not affect the result in terms of the optimal dynamic tax schedule. In both cases, we observe that the optimal labor tax declines over time, while the optimal robot tax is initially (virtually) zero and increases over time.

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A Tables

Table (3) Public education spending; Basic: primary + secondary education spending; High: tertiary education spending

	<i>Dependent variable:</i>					
	skill_premium					
	(1)	(2)	(3)	(4)	(5)	(6)
PUB_EDUEXP	0.046*** (0.013)	0.046*** (0.013)				
PUB_BASIC_EDUEXP			0.049*** (0.016)	0.052*** (0.016)		
PUB_HIGH_EDUEXP					0.182*** (0.034)	0.183*** (0.034)
country fixed effects	✓	✓	✓	✓	✓	✓
time trend	✓	✓	✓	✓	✓	✓
country-spec. time trend	✓	✓	✓	✓	✓	✓
private education spending		✓		✓		✓
Observations	394	394	402	402	418	418
R ²	0.962	0.962	0.960	0.961	0.957	0.957
Adjusted R ²	0.957	0.957	0.955	0.955	0.952	0.952

Note:

*p<0.1; **p<0.05; ***p<0.01

Table (4) X: log of education spending per student (data: Education Finance Statistics of United States (Knoema)); Y = inequality measures from Franks paper; US by State analysis

	<i>Dependent variable:</i>									
	Atkin05		Gini		RMeanDev		Theil		Top10_adj	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
X	0.019*** (0.005)	0.029*** (0.006)	0.038*** (0.007)	0.080*** (0.008)	0.016*** (0.006)	0.056*** (0.006)	0.071*** (0.027)	0.086*** (0.031)	-1.298* (0.689)	2.270*** (0.791)
State fixed effects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
time trend	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
State-spec. time trend		✓		✓		✓		✓		✓
Observations	935	935	935	935	935	935	935	935	935	935
R ²	0.848	0.868	0.708	0.776	0.906	0.935	0.869	0.888	0.867	0.892
Adjusted R ²	0.839	0.851	0.691	0.748	0.900	0.927	0.861	0.874	0.859	0.879

Note:

*p<0.1; **p<0.05; ***p<0.01

Table (5) X: log of education spending per student (data: Education Finance Statistics of United States (Knoema)); Y = log of GDP. US by State analysis

	<i>Dependent variable:</i>			
	Y			
	(1)	(2)	(3)	(4)
X	0.159*** (0.021)	0.265*** (0.015)	3.785*** (0.371)	3.013*** (0.402)
X ²			−0.196*** (0.020)	−0.152*** (0.022)
State fixed effects	✓	✓	✓	✓
time trend	✓	✓	✓	✓
State-spec. time trend		✓		✓
Observations	935	935	935	935
R ²	0.998	0.999	0.998	0.999
Adjusted R ²	0.998	0.999	0.998	0.999

Note: *p<0.1; **p<0.05; ***p<0.01

B Theoretical model

B.1 Equilibrium conditions

We assume that type-specific aggregate labor supply can be calculated as the type-specific individual labor supply multiplied with the number of type-specific agents:

$$\tilde{H}_{Y,t} = (1 - \eta - z_{H,t}) H_{Y,t}, \quad (22)$$

$$\tilde{H}_{A,t} = (1 - \eta - z_{H,t}) H_{A,t}, \quad (23)$$

and

$$\tilde{L}_t = (1 - z_{L,t}) L_t. \quad (24)$$

Aggregate high-skilled labor supply is defined as the sum of aggregate high-skilled labor supplied in the final production and R&D sector

$$\tilde{H}_t = \tilde{H}_{Y,t} + \tilde{H}_{A,t}. \quad (25)$$

The total number of high-skilled individuals is the sum of high-skilled individuals working in the final production sector and the researchers (the high-skilled individuals working in the R&D sector):

$$H_t = H_{Y,t} + H_{A,t}. \quad (26)$$

Overall, the number of high-skilled and low-skilled individuals needs to sum up to (the constant population size) N in all model periods:

$$N = H_t + L_t. \quad (27)$$

To close the model economy, we impose a no-arbitrage condition on high-skilled wage rates in both final good and R&D sector:

$$w_{H,t} = w_{A,t}. \quad (28)$$

B.2 Proofs

Redistribution channel Consider a change in the labor tax (τ_W):

$$\left. \frac{d c_H/c_L}{d \tau_W} \right|_{\text{RE}} = \underbrace{\frac{\partial c_H/c_L}{\partial \tau_W}}_{\text{RE}_W(1)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_W}}_{\text{RE}_W(2)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j' \in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j'' \in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_W}}_{\text{RE}_W(3)} \quad (29)$$

where:

$$\text{RE}_W(1) = \frac{-(1 - \eta)w_h \left[(1 - \tau_W)w_L + \hat{T}_L \right] + w_L \left[(1 - \tau_W)(1 - \eta)w_H + \hat{T}_H \right]}{\left[(1 - \tau_W)w_L + \hat{T}_L \right]^2}, \quad (30)$$

which is positive if $\omega < \frac{w_L L_L}{(1-\eta)w_H L_H + w_L L_L} \equiv \tilde{\omega}$;

$$\text{RE}_W(2) = \frac{\partial c_H/c_L}{\partial \hat{T}_H} \frac{\partial \hat{T}_H}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_W} + \frac{\partial c_H/c_L}{\partial \hat{T}_L} \frac{\partial \hat{T}_L}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_W} \quad (31)$$

where $\frac{\partial \mathcal{G}}{\partial \tau_W}$ is always positive. This implies that $\text{RE}_W(2) > 0$ if:

$$\frac{\partial c_H/c_L}{\partial \hat{T}_H} \frac{\partial \hat{T}_H}{\partial \mathcal{G}} + \frac{\partial c_H/c_L}{\partial \hat{T}_L} \frac{\partial \hat{T}_L}{\partial \mathcal{G}} > 0 \quad (32)$$

where:

$$\frac{\partial c_H/c_L}{\partial \hat{T}_H} \frac{\partial \hat{T}_H}{\partial \mathcal{G}} = \frac{1}{(1-\tau_W)w_L + \hat{T}_L} \cdot \frac{(1-\omega)(1-\phi)}{H} \quad (33)$$

and

$$\frac{\partial c_H/c_L}{\partial \hat{T}_L} \frac{\partial \hat{T}_L}{\partial \mathcal{G}} = - \frac{(1-\tau_W)(1-\eta)w_H + \hat{T}_H}{[(1-\tau_W)w_L + \hat{T}_L]^2} \cdot \frac{\omega(1-\phi)}{L}. \quad (34)$$

Substituting $\hat{T}_H = \frac{(1-\omega)(1-\phi)}{H} \mathcal{G}$ and $\hat{T}_L = \frac{\omega(1-\phi)}{L} \mathcal{G}$, we obtain that $\text{RE}_W(2) > 0$ if $\omega < \tilde{\omega}$;

$$\text{RE}_W(3) = \left(\frac{\partial c_H/c_L}{\partial \hat{T}_H} \frac{\partial \hat{T}_H}{\partial \mathcal{G}} + \frac{\partial c_H/c_L}{\partial \hat{T}_L} \frac{\partial \hat{T}_L}{\partial \mathcal{G}} \right) \underbrace{\sum_{j' \in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j'' \in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_W}}_D.$$

Since $D > 0$, $\text{RE}_W(3) > 0$ if $\frac{\partial c_H/c_L}{\partial \hat{T}_H} \frac{\partial \hat{T}_H}{\partial \mathcal{G}} + \frac{\partial c_H/c_L}{\partial \hat{T}_L} \frac{\partial \hat{T}_L}{\partial \mathcal{G}} > 0$ which is the same condition that implies $\text{RE}_W(2) > 0$. Therefore, $\text{RE}_W(3) > 0$ if $\omega < \tilde{\omega}$. From the above, we obtain that: $\left. \frac{d c_H/c_L}{d \tau_W} \right|_{\text{RE}} < 0$ iff $\omega > \tilde{\omega}$.

Consider a change in the robot tax (τ_R):

$$\left. \frac{d c_H/c_L}{d \tau_R} \right|_{\text{RE}} = \underbrace{\frac{\partial c_H/c_L}{\partial w_H} \frac{\partial w_H}{\partial \tau_R}}_{\text{RE}_R(1)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \frac{\partial \mathcal{G}}{\partial \tau_R}}_{\text{RE}_R(2)} + \underbrace{\sum_{j \in H,L} \frac{\partial c_H/c_L}{\partial \hat{T}_j} \frac{\partial \hat{T}_j}{\partial \mathcal{G}} \sum_{j' \in H,L} \frac{\partial \mathcal{G}}{\partial w_{j'}} \sum_{j'' \in H,L} \frac{\partial w_{j'}}{\partial h_{j''}} \frac{\partial h_{j''}}{\partial \tau_R}}_{\text{RE}_R(3)}. \quad (35)$$

Following the same steps as for the labor tax, we find that $\text{RE}_R(2)$ and $\text{RE}_R(3)$ are negative if $\omega > \tilde{\omega}$. $\text{RE}_R(1)$ is instead always negative. This implies that a sufficient condition for $\left. \frac{d c_H/c_L}{d \tau_R} \right|_{\text{RE}}$ to be negative is $\omega > \tilde{\omega}$.

Human capital channel Consider a change in either the labor or the robot tax, i.e., $g \in \{W, R\}$:

$$\left. \frac{d w_H/w_L}{d \tau_g} \right|_{\text{HC}} = \underbrace{\frac{\partial w_H/w_L}{\partial h_H/h_L} \frac{\partial h_H/h_L}{\partial \tau_g}}_{\text{HC}_g(1)} + \underbrace{\frac{\partial w_H/w_L}{\partial \tilde{A}} \frac{\partial \tilde{A}}{\partial h_H} \frac{\partial h_H}{\partial \tau_g}}_{\text{HC}_g(2)}. \quad (36)$$

We can write the wage and human capital ratios as:

$$\frac{w_H}{w_L} = \frac{1-\alpha}{\alpha} \frac{L_L}{L_H} \left[1 + \tilde{A} \left(\frac{\alpha^2}{\tilde{R}(1+\tau_R)} \right)^{\frac{\alpha}{1-\alpha}} \left(\frac{h_H L_H}{h_L L_L} \right)^\alpha \right], \quad (37)$$

$$\frac{h_H}{h_L} = \frac{B_H}{B_L^{\mu_H}} \left(\frac{\phi_B \cdot \phi}{N} \right)^{-\mu_L \mu_H} \left(\frac{(1 - \phi_B) \phi}{H} \right)^{\mu_H} \mathcal{G}^{\mu_H(1-\mu_L)} \quad (38)$$

Since $\frac{\partial \mathcal{G}}{\partial \tau_g} > 0$, then $\frac{\partial h_H/h_L}{\partial \tau_g} > 0$. Therefore, since also $\frac{\partial w_H/w_L}{\partial h_H/h_L} > 0$, $\text{HC}_g(1) > 0$. Moreover, since all the three terms in the second term of equation (36) are positive, $\text{HC}_g(2)$ and $\left. \frac{d}{d\tau_g} \frac{w_H/w_L}{\tau_g} \right|_{\text{HC}}$ are positive.

B.3 Private college education spending

When we allow high-skilled households to invest privately into higher education, (3), (4) and (4) change to

$$c_{j,t} = \frac{1}{1 + \beta + \gamma} \left((1 - \tau_W)(1 - \eta_j)w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]} \theta_t \right), \quad (39)$$

$$s_{j,t} = \frac{\beta}{1 + \beta + \gamma} \left((1 - \tau_W)(1 - \eta_j)w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]} \theta_t \right), \quad (40)$$

and

$$z_{j,t} = \frac{\gamma}{(1 + \beta + \gamma)(1 - \tau_W)w_{j,t}} \left((1 - \tau_W)(1 - \eta_j)w_{j,t} + \hat{T}_{j,t} - \mathbb{1}_{[j=H]} \theta_t \right). \quad (41)$$

From solving the indifference condition, we obtain the same functional form as in (5).

Perfect substitutability of private and public spending on higher education Under the assumption of perfect substitutability between private and public spending on higher education, (17) breaks down to

$$h_{H,t} = B_H \cdot (h_{B,t})^{1-\mu_H} \cdot \left(\theta_t + \hat{E}_{H,t} \right)^{\mu_H}, \quad (42)$$

leading to a much simpler expression for

$$\frac{\partial h_{H,t}}{\partial \theta_t} = B_H \cdot \mu_H \cdot \left(\frac{h_{B,t}}{\theta_t + \hat{E}_{H,t}} \right)^{1-\mu_H}.$$