DISCUSSION PAPER SERIES

Discussion paper No.272

Taxation of a Non-renewable Resource and Inequality in an R&D-based Growth Model

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May 2024

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Abstract

This paper analyses the effects of resource taxation policies aimed at sustainable use of resources on economic growth and consumption inequality using an R&D-based growth model with heterogeneous households. Resource taxes affect the extraction rate of non-renewable resources only if the tax rate changes over time. This paper shows that the lower growth rate of the ad valorem tax on resource use slows resource extraction and promotes economic growth but increases consumption inequality. If resource tax policies are to promote economic growth without increasing consumption inequality, resource tax revenues must be allocated for redistributive purposes. This paper also calibrates the model for quantitative analysis and finds that the lower growth rate of the tax on resource use causes a non-negligible increase in consumption inequality.

Keywords: Non-renewable resources, Endogenous growth, Consumption inequality, R&D
JEL Classification: E62, H23, O30, Q32, Q38

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Acknowledgements: This research was financially supported by KIER joint research program and the Japan Society for the Promotion of Science: Grants-in-Aid for Scientific Research (C) 20K01569

1 Introduction

To avert a climate crisis and address the issue of resource scarcity, many governments around the world are implementing market-based policies (e.g., carbon taxes, cap-and-trade systems, fossil fuel taxes, and subsidy reforms) aimed at affecting resource prices and reducing incentives for fossil fuel use.[1] In the field of resource economics, the exploitation of fossil resources raises two concerns. One is the link between the scarcity of fossil resources and sustainable growth, and the other is the negative externalities associated with the use of fossil resources (e.g., greenhouse gas emissions). Since the pioneering contributions of Dasgupta and Heal (1974), Solow (1974), and Stiglitz (1974), a vast literature has studied taxation on resource use in the context of general equilibrium growth models where technological progress plays an effective role in ensuring sustainable consumption in the long run (e.g., Grimaund and Rouge, 2004, 2008, 2014; Groth and Schou, 2007; Daubanes and Grimaund, 2010; Pittel and Bretschger, 2010; Hori and Yamagami, 2018). The main objectives of these studies are to determine (1) whether and under what circumstances resource taxation is effective in ensuring sustainable growth and (2) how resource taxes can be designed to achieve socially desirable resource exploitations. However, these studies have not considered natural resources as assets and have paid little attention to the distributional implications of resource taxation policies, even though they are crucial to developing policies that are socially acceptable and avoid negative impacts on the poor. Therefore, in this study, we explore the effect of resource taxation policy on economic growth and consumption inequality. Note that consumption inequality is the most relevant measure of inequality from an economic welfare perspective because it reflects lifetime income inequality (e.g., Krueger and Perri, 2006; Attanasio and Pistaferri, 2016). We find that tax policies aimed at decreasing the speed of resource extraction have regressive policy implications.

The growth-theoretic framework that we consider is Grossman and Helpman's (1991, ch3) expanding-input-variety model with exhaustible natural resources (e.g., Grimaud and Rouge 2004, 2008, 2014; Daubanes and Grimaund, 2010; Pittel and Bretschger, 2010). We extend this model by allowing for heterogeneous households with different levels of asset holdings. In this growth-theoretic framework, we find that the lower growth rate of the ad valorem tax on resource use slows resource extraction and promotes economic growth but increases consumption inequality. Piketty (2014) suggests that an unequal distribution of wealth is an important determinant of lifetime income inequality. In our model, the effect of resource taxation policy on consumption inequality depends on the rate of return on assets, which is determined by the interaction between the arbitrage condition on assets and the Hotelling rule that characterizes the depletion path of exhaustible resources. Therefore, even if natural resources do not represent a large share of assets in reality, the effect of resource taxation policy on consumption inequality remains significant in the presence of other capital income that depends on the real interest rate.

Under the standard formulation of depletable resources, resource taxes affect the extraction rate of non-renewable resource only if the tax rate changes over time (e.g., Withagen 1994; Sinclair 1992; Groth and Snou 2007; Grimaud and Rouge 2004, 2008, 2014). A lower growth rate of the ad valorem tax on resource use induces a slowdown in resource

[1] It is well known that a large portion of greenhouse gas emissions come from the combustion of exhaustible fossil fuels. Carbon dioxide from fossil fuel use and industrial processes represents 65% of 2010 global greenhouse gas emissions (IPCC 2014). Fossil fuel combustion also generates nitrous oxide (N2O), which accounted for 6% of 2010 global greenhouse gas emissions.

extraction because resource owners foresee a future increase in the non-taxed shares of resource revenues. This slower rate of resource extraction mitigates the negative impact of resource scarcity on economic growth, which in turn increases economic growth. When the lower growth rate of the resource tax leads to higher economic growth, the real interest rate also rises, widening the gap between the real interest rate and the economic growth rate under empirically plausible values of intertemporal substitution. As Piketty (2014) argues, the gap between the real interest rate and the economic growth rate crucially affects the distribution of wealth and thus consumption inequality because inherited wealth grows faster than labour income, resulting in a highly concentrated distribution of wealth. As a result, a lower growth rate of the resource tax has a positive effect on consumption inequality by widening the gap between the real interest rate and the economic growth rate. Furthermore, a lower growth rate of the resource tax has an additional positive effect on consumption inequality by reducing R&D activities and slowing the growth rate of real wages. A lower growth rate of the resource tax has two competing effects on R&D activities. On the one hand, it enhances economic growth, promotes growth in the size of the market for new intermediate inputs inventions, and stimulates R&D activities. On the other hand, it increases the real interest rate, which lowers the present value of new inventions by increasing the discount rate and discourages R&D activities. Since the latter negative effect always dominates the former positive effect under empirically plausible values of intertemporal substitution, a lower growth rate of the resource tax discourages R&D activities, suppresses real wage growth, and positively affects consumption inequality.

This paper also examines how allocating resource tax revenues for redistributive purposes affects economic growth and consumption inequality. We show that increasing the degree of redistribution in government transfers to households can lower consumption inequality without impeding economic growth. Finally, we present some numerical examples of our model to investigate the quantitative effects of resource taxation policy on economic growth and consumption inequality. We find that a lower growth rate of the tax on resource use causes a non-negligible increase in consumption inequality. Therefore, if resource tax policies are to promote economic growth without increasing consumption inequality, resource tax revenues must be allocated for redistributive purposes.

This paper is closely related to the following three branches of the literature. First, this paper is related to studies analysing the optimal taxation of polluting nonrenewable resources. Early works (e.g., Withagen 1994; Sinclair 1992; Ulph and Ulph 1994) use partial equilibrium models of depletable resources in which the use of a resource results in the accumulation of a stock of pollution that negatively affects production and utility. More recent works (e.g., Grimaud and Rouge 2004, 2008, 2014; Daubanes and Grimaund, 2010; Pittel and Bretschger, 2010) address this issue using general equilibrium models with endogenous growth and show that resource extraction under a decentralized equilibrium is generally faster than optimal, that this distortion is corrected by a decreasing ad valorem tax on resource use, and that this optimal policy delays resource depletion and promotes economic growth. Our paper's findings on the relationship between resource taxation policies and economic growth are consistent with the findings of these studies. In contrast to previous work, this paper employs a model that allows for heterogeneous households with different assets and rigorously examines the effect of resource taxation on consumption inequality.

Second, this paper relates to studies that have analysed the distributional impacts of market-based climate policies without reaching a clear consensus. Early empirical studies of developed countries estimate that environmental taxes are strongly regressive (e.g., Metcalf 1999, 2009; Wier et al. 2005). They highlight the fact that poor households seem to devote a larger share of their disposable income to energy. However, more recent works question the methodology used to obtain these results. Studies using other measures empirically estimate that environmental taxes are less regressive and even more progressive (e.g., Cronin et al. 2017; Sterner 2012). Ohlendorf (2021) provides a comprehensive survey of empirical studies and notes that empirical findings on the distributional effects of climate policy are mixed. Furthermore, numerical simulation analyses using general equilibrium models emphasize that environmental taxes have a significant impact on household income formation through changes in factor prices such as relative wages and capital income. A recent study by Känzig (2022) provides regressive simulation results, while other studies support progressivity (e.g., Dissou and Siddiqui 2014; Mathur and Morris 2014). Compared to these studies that have analysed the relatively short-term distributional effects of environmental policies, only a few papers have analysed the long-term distributional effects of environmental policies using the growth-theoretic framework. Spinesi's (2022) is an exceptional study that analyses the impact of environmental tax policies on income inequality between skilled and unskilled workers using a Schumpeterian R&D growth model. Spinesi (2022) shows that when a low share of the environmental tax is levied on consumption, a tighter environmental tax results in an increase in individuals' human capital accumulation and income inequality between skilled and unskilled workers and spurs the economic growth rate. In contrast to these studies, this paper focuses on the aspect of natural resources as assets and examines the long-run distributional implications of resource taxation policy. In this sense, this paper sheds light on the distributional effects of resource taxation policies that have not yet been analysed.

Third, this paper is related to studies that explore the effects of policy interventions on the relationship between economic growth and lifetime income inequality in the R&D based growth model (e.g., Chu 2010; Chu and Cozzi 2018; Chu et al. 2019; Basu and Gatachew 2019; Morimoto and Tabata 2020; Chu et al 2021). For example, Chu (2010), Chu and Cozzi (2018) and Chu et al (2021) explore the effects of patent and R&D policies, Chu et al. (2019) explore the effects of monetary policy, Basu and Gatachew (2019) explore the effects of redistributive policy, and Morimoto and Tabata (2020) explore the effects of higher education policy. However, the effect of resource taxation policy has yet to be rigorously examined in the literature. Therefore, our research complements these existing studies and tackles an issue that has gone unexplored in the literature.

The remainder of this paper is organized as follows. Section 2 presents the basic model. Section 3 examines the effects of resource taxation on economic growth. Section 4 investigates the effects of resource taxation on consumption inequality. Section 5 provides a quantitative analysis. Section 6 discusses several extensions of the model. Section 7 concludes the paper.

2 Model

In this section, we extend Grossman and Helpman's (1991, cH 3) expanding-input-variety model with exhaustible natural resources to allow for heterogeneous households with different assets. We examine how taxation of exhaustible resource use affects growth and inequality. As in most R&D-based endogenous growth models with exhaustible resources, we assume that exhaustible resources are an essential factor of production but that labour is the only input to R&D. For production, there are four sectors: a non-renewable resource sector, a final goods sector, an intermediate goods sector, and a R&D sector. The government taxes resource use for production and distributes resource tax revenues to households.

2.1 Non-renewable resource sector

The non-renewable resource is extracted from an initial finite stock S_0. At each date t, resource stock S_t is depleted by the extraction of resources H_t for production, such that the dynamics of the resource stock are

$$\dot{S}_t = -H_t. \tag{1}$$

The value of a representative resource firm is determined as the present value of the future profit stream:

$$v_t^s = \int_t^{\infty} p_{H,s} H_s e^{-\int_t^s r_u du} ds, \tag{2}$$

where $p_{H,t}$ is the price of resources and r_t is the interest rate. On the competitive natural resource market, a representative resource firm maximizes (2) subject to (1), which yields the familiar Hotelling rule:[2]

$$\frac{\dot{p}_{H,t}}{p_{H,t}} = r_t. \tag{3}$$

As usual, the transversality condition implies that $\lim_{t\to\infty} S_t = 0$ and $\int_t^{\infty} H_s ds = S_t$. Using (2), (3) and $\int_t^{\infty} H_s ds = S_t$, the value of a representative resource firm is given by

$$v_t^s = p_{H,t} S_t. \tag{4}$$

Under the assumption that resources are extracted at no cost (e.g., Grimaund and Rouge, 2004, 2014; Groth and Schou, 2007; Daubanes and Grimaund, 2010; Hori and Yamagami 2018), the value of a representative resource firm is expressed as the product of the resource price $p_{H,t}$ and the amount of remaining resources S_t.

In the following analysis, to avoid unnecessary complications, we do not explicitly consider negative externalities associated with the use of natural resources, such as pollution stocks that adversely affect production and utility. Such an extension would not significantly change our main results regarding the effects of resource tax policies on consumption inequality.

2.2 Final good

A competitive firm produces final good Y_t using the following production function:

$$Y_t = \left(\int_0^{N_t} x_{i,t}^{\frac{\epsilon-1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon-1}}, \tag{5}$$

where $x_{i,t}$ denotes the quantity of non-durable intermediate good $i \in [0, N_t]$, N_t is the mass of available intermediate goods at time t, and the parameter $\epsilon > 1$ indicates the elasticities of substitution across intermediate goods. A higher ϵ indicates the existence of greater substitutability between the intermediate inputs.

[2] Equation (3) states that the resource owner's net rent $\dot{p}_{H,t}/p_{H,t}$ is equal to the interest rate r_t.

With final goods as our $numeraire$, the conditions for profit maximization in the competitive final goods sector yield the following conditional demand function for $x_{i,t}$:

$$x_{i,t} = \frac{p_{i,t}^{-\epsilon}}{\int_0^{N_t} p_{i,t}^{1-\epsilon} di} Y_t, \tag{6}$$

where $p_{i,t}$ is the price of $x_{i,t}$. Competitive producers of the final good pay $Y_t = \int_0^{N_t} p_{i,t} x_{i,t} di$ for intermediate goods.

2.3 Intermediate goods

The monopolistic firm in industry i produces the differentiated intermediate good with the following constant-returns-to scale production technology:

$$x_{i,t} = l_{i,t}^{1-\alpha} h_{i,t}^{\alpha} \tag{7}$$

where $l_{i,t}$ and $h_{i,t}$ denote labour and resource inputs, respectively, and the parameter $\alpha \in (0, 1)$ represents the resource intensity. A large (small) α indicates a strong (weak) dependence of natural resources in production. Since the production function (7) is a Cobb-Douglas form, the unit cost function of the intermediate good is given by

$$\omega_t = w_t^{1-\alpha} \left[(1 + \varphi_t) p_{H,t} \right]^{\alpha}, \tag{8}$$

where w_t is the wage rate and φ_t is the unit ad valorem tax/subsidy on resource use. Henceforth, we will denote $\tau_t \equiv 1 + \varphi_t$ for computational convenience.[3] If $\tau_t < 1$ (i.e., $\varphi_t < 0$), the government subsidizes resource use for production at time t, and if $\tau_t > 1$ (i.e., $\varphi_t > 0$), the government taxes resource use for production at time t. In the following analysis, we restrict our analysis to the case where τ_t evolves over time at constant value and is not too decreasing over time. That is, $\gamma_{\tau,t} \equiv \dot{\tau}_t / \tau_t$ and $\gamma_{\tau,t} = \gamma_\tau \geq -\rho$, for $\forall t \in [0, \infty)$. Therefore, the resource tax is given by $\tau_t = \tau_0 e^{\gamma_\tau t}$. Following Daubanes and Grimaund (2010), we examine the impact of changes in the tax level τ_0 and the impact of changes in the tax growth rate γ_τ. Later, Proposition 1 will show that the assumption that the tax growth rate is constant is necessary to derive an analytically tractable equilibrium growth path.

In industry i, the monopolistic firm's profit flow at time t is

$$\pi_{i,t} = (p_{i,t} - \omega_t)\, x_{i,t}. \tag{9}$$

The value of monopolistic firm in industry i is $v_{i,t} = \int_t^\infty \pi_{i,s} e^{-\int_t^s r_u du} ds$. The monopolistic firm in industry i maximizes (9) subject to (6). The profit-maximizing price and the equilibrium profit of a monopolistic firm in industry i are given by

$$p_{i,t} = \frac{\epsilon}{\epsilon - 1} \omega_t \equiv p_t, \tag{10}$$

$$\pi_{i,t} = \frac{1}{\epsilon} \frac{Y_t}{N_t} \equiv \pi_t. \tag{11}$$

Because of the ex ante homogeneity, the size (the value) of intermediate good firms is also identical across all industries such that $x_{i,t} = x_t$ ($v_{i,t} = v_t$). Therefore, in the following analysis, we omit index i whenever this does not lead to confusion.

[3] In what follows, we may prefer to use the multiplicative rate τ_t instead of the ad valorem rate φ_t.

2.4 R&D

The intermediate sector buys patents from the research sector at their market value v_t. The production function for blueprints is given by $\dot{N}_t = \varphi N_t L_{R,t}$, where $L_{R,t}$ is the amount of labour employed in the R&D sector and φ is the productivity parameter. Following Romer (1990), we assume that the stock of existing blueprints positively affects the productivity of researchers (i.e., standing on the shoulders of giants). Since the R&D sector is competitive, the price of a new blueprint v_t is equal to the marginal cost of producing it:[4]

$$v_t = \frac{w_t}{\varphi N_t}. \tag{12}$$

The existence of several assets (i.e., bonds, patents, and shares of resource firms) implies that their rates of return must be equal in equilibrium. Indeed, by differentiating $v_t = \int_t^\infty \pi_s e^{-\int_t^s r_u du} ds$ with t, we have

$$r_t = \frac{\pi_t + \dot{v}_t}{v_t}. \tag{13}$$

The return on blueprints is the dividend plus the capital gain expressed in terms of the purchase price of the blueprint.

2.5 Heterogeneous households

There is a unit continuum of households, which are indexed by $h \in [0, 1]$. They have identical homothetic preferences over consumption $C_s(h)$ but own different levels of wealth. Household h has the following utility function:

$$U_t(h) = \int_t^\infty \frac{C_s(h)^{1-\sigma}}{1-\sigma} e^{-\rho(s-t)} ds, \tag{14}$$

where the parameter $\sigma > 0$ is the inverse of the intertemporal substitution and $\rho > 0$ is the subjective discount rate.[5] To ensure that lifetime utility is bounded, the following parameter restriction is imposed on the discount rate: $\rho > (1-\sigma)\gamma_C^*$, where γ_C^* denotes the steady state growth rate of consumption explained later.

Household h maximizes (14) subject to

$$\int_t^\infty C_s(h) e^{-\int_t^s r_u du} ds = \int_t^\infty \left[w_s L + T_s(h)\right] e^{-\int_t^s r_u du} ds + A_t(h), \tag{15}$$

where $A_t(h)$ is the value of private assets owned by household h and $T_t(h)$ is a lump-sum tax/transfer of household h. Household h supplies L units of labour to earn wage rate w_t.

From standard dynamic optimization, the familiar Euler equation is

$$\frac{\dot{C}_t(h)}{C_t(h)} = \frac{1}{\sigma}\left(r_t - \rho\right), \tag{16}$$

which shows that the growth rate of consumption is the same across households such that $\dot{C}_t(h)/C_t(h) = \dot{C}_t/C_t = (1/\sigma)(r_t - \rho)$, where $C_t \equiv \int_0^1 C_t(h) dh$ is aggregate consumption. The market-clearing condition of final goods $Y_t = C_t$ indicates that the relation $\gamma_{Y,t} = \gamma_{C,t}$ holds, where $\gamma_{Y,t} \equiv \dot{Y}_t/Y_t$ and $\gamma_{C,t} \equiv \dot{C}_t/C_t$.

[4] We restrict our analysis to the case where R&D investment is always positive (i.e., $L_{R,t} > 0$).

[5] If $\sigma = 1$, the lifetime utility of the household h becomes $U_t(h) = \int_t^\infty lnC_s(h) e^{-\rho(s-t)} ds$.

2.6 Government

The government budget constraint consists of two components: a tax/subsidy on resource use for production $(\tau_t - 1)\, p_{H,t} H_t$ and a lump-sum tax/transfer of household $T_t(h)$. Assuming that it is balanced at each date t, the government budget constraint is given by

$$(\tau_t - 1)\, p_{H,t} H_t - T_t = 0. \tag{17}$$

where $T_t = \int_0^1 T_t(h) dh$ and $\tau_t = \tau_0 e^{\gamma_\tau t}$.

2.7 Labour and resource markets

Each intermediate good firm demands $(\partial \omega_t / \partial w_t) x_t$ units of labour and $(\partial \omega_t / \partial (\tau_t p_{H,t})) x_t$ units of exhaustible resources. The labour demand of R&D firms is equal to $(1/\varphi)\gamma_{N,t}$, where $\gamma_{N,t} \equiv \dot{N}_t / N_t$. Using (6), (8), and (10), the labour and resource market equilibrium conditions are given by

$$L = \frac{(1-\alpha)(\epsilon - 1)}{\epsilon} \frac{Y_t}{w_t} + \frac{\gamma_{N,t}}{\varphi}, \tag{18}$$

$$H_t = \frac{\alpha(\epsilon - 1)}{\epsilon} \frac{Y_t}{\tau_t p_{H,t}}. \tag{19}$$

2.8 Asset market

In equilibrium, taking into account (4) and $v_t = \int_t^\infty \pi_s e^{-\int_t^s r_u du} ds$, the value of private assets owned by household h is given by

$$A_t(h) = v_t^S(h) + v_t N_t(h) = p_{H,t} S_t(h) + v_t N_t(h), \tag{20}$$

where $v_t^S(h)$ is the shares of resource firms owned by household h, $N_t(h)$ is the amount of patents owned by household h, and $S_t(h)$ is the amount of resources held by household h through its ownership of shares of resource firms.

The value of all existing resource firms shares and patents add to the value of household private assets such that

$$A_t = v_t^S + v_t N_t = p_{H,t} S_t + v_t N_t, \tag{21}$$

where $v_t^S = \int_0^1 v_t^S(h) dh$, $A_t = \int_0^1 A_t(h) dh$, $S_t = \int_0^1 S_t(h) dh$ and $N_t = \int_0^1 N_t(h) dh$.

3 Equilibrium dynamics, resource taxation, and growth

In this section, we explore the effect of resource taxation on the aggregate growth rate of the economy. Section 3-1 shows that the aggregate economy always jumps to a unique balanced growth path. Section 3-2 examines how the resource tax growth rate γ_τ and the resource tax level τ_0 affect the rate of resource extraction and economic growth.

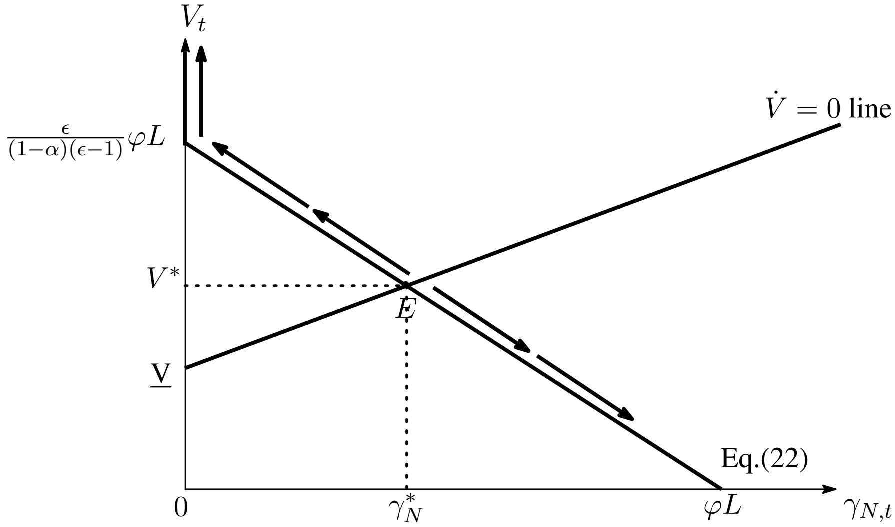

Figure 1: Phase diagram

3.1 Dynamics of aggregate economy

To obtain the equilibrium, we define $V_t \equiv Y_t/(v_t N_t)$, where $v_t N_t$ is the economy's aggregate patent value and Y_t is the aggregate final goods production (i.e., the market size of intermediate goods). Thus, V_t represents the inverse measure of the patent value adjusted by its market size. The appendix A shows that the dynamic system is composed of the following two equations:

$$\gamma_{N,t} = \varphi L - \frac{(1-\alpha)(\epsilon-1)}{\epsilon} V_t, \tag{22}$$

$$\frac{\dot{V}_t}{V_t} = \frac{1-\alpha+\alpha\sigma}{\sigma}\left[\frac{V_t}{\epsilon} + \frac{\alpha(\sigma-1)}{1-\alpha+\alpha\sigma}\gamma_\tau - \frac{1+(\sigma-1)\left(\alpha+\frac{1}{\epsilon-1}\right)}{1-\alpha+\alpha\sigma}\gamma_{N,t} - \frac{\rho}{1-\alpha+\alpha\sigma}\right]. \tag{23}$$

Using a phase diagram, we derive the steady state equilibrium, in which V_t is constant over time. Substituting $\dot{V}_t = 0$ into (23) yields

$$V_t = \epsilon\left[\frac{1+(\sigma-1)\left(\alpha+\frac{1}{\epsilon-1}\right)}{1-\alpha+\alpha\sigma}\gamma_{N,t} + \frac{\rho}{1-\alpha+\alpha\sigma} - \frac{\alpha(\sigma-1)}{1-\alpha+\alpha\sigma}\gamma_\tau\right]. \tag{24}$$

Figure 1 shows the graphs of (22) and (24). The intersection of the two graphs converges to a steady state. The graph of (24) intersects with the vertical axis at $\underline{V} \equiv [\rho - \alpha(\sigma-1)\gamma_\tau]/(1-\alpha+\alpha\sigma)$. Therefore, if $\underline{V} < \epsilon\varphi L/[(1-\alpha)(\epsilon-1)]$, which is equivalent to $\varphi L > (1-\alpha)(\epsilon-1)\left[\rho - \alpha(\sigma-1)\gamma_\tau\right]/(1-\alpha+\alpha\sigma)$, the two graphs intersect at a point at which γ_N^* is strictly positive (i.e., $\gamma_N^* > 0$). An asterisk is used to indicate a variable in the steady state. Because the steady state is unstable and V_t and $\gamma_{N,t}$ are jump variables, these variables are always in their steady states. We now prove the next proposition.

Proposition 1 *Suppose that when the resource tax growth rate is constant over time (i.e., $\gamma_{\tau,t} = \gamma_\tau$), the economy jumps to its steady state in which the following hold:*

$$\gamma_{N,t} = \frac{\varphi L + \frac{(1-\alpha)(\epsilon-1)}{1-\alpha+\alpha\sigma}\left[\alpha(\sigma-1)\gamma_\tau - \rho\right]}{\frac{\sigma}{1-\alpha+\alpha\sigma} + (1-\alpha)(\epsilon-1)} \equiv \gamma_N^*, \tag{25}$$

$$\gamma_{H,t} = -\frac{\frac{\sigma-1}{\epsilon-1}\gamma_N^* + \gamma_\tau + \rho}{1-\alpha+\alpha\sigma} \equiv -\gamma_H^*, \tag{26}$$

$$H_t = \gamma_H^* S_t = \gamma_H^* S_0 e^{-\gamma_H^* t}, \tag{27}$$

$$\gamma_{Y,t} = \frac{\gamma_N^*}{\epsilon-1} - \alpha\gamma_H^* = \frac{\frac{\gamma_N^*}{\epsilon-1} - \alpha(\gamma_\tau+\rho)}{1-\alpha+\alpha\sigma} \equiv \gamma_Y^*, \tag{28}$$

$$r_t = \sigma\gamma_Y^* + \rho \equiv r^*. \tag{29}$$

Proof: See Appendix B.

To ensure that the transversality condition holds, we confine our analysis to the case where the following inequality holds: $\gamma_{H,t} = -\gamma_H^* < 0$. From (26), if $\sigma \geq 1$, the relation $\gamma_{H,t} = -\gamma_H^* < 0$ holds. Even if $\sigma < 1$, the inequality $\gamma_{H,t} = -\gamma_H^* < 0$ holds as long as the relation $[(\sigma-1)/(\epsilon-1)]\gamma_N^* + \gamma_\tau + \rho > 0$ holds. Since most empirical evidence suggests that the intertemporal elasticity of substitution is relatively small (e.g., Guvenen 2006), we mainly analyse the case of $\sigma \geq 1$, but we also mention the results for $\sigma < 1$ to facilitate an intuitive understanding of the theoretical results.

Proposition 1 shows that as long as the resource tax growth rate is constant over time (i.e., $\gamma_{\tau,t} = \gamma_\tau$), the product variety growth rate $\gamma_{N,t}$, the resource extraction rate $\gamma_{H,t}$, the output growth rate $\gamma_{Y,t}$, and the interest rate r_t immediately jump to their steady state values. The level of resource extraction H_t gradually approaches zero at a constant rate in the long run (i.e., $\lim_{t\to\infty} H_t = 0$). From (28), we see that a positive output growth rate is possible only if the relation $\gamma_N^* > \alpha(\epsilon-1)(\gamma_\tau+\rho)$ holds. This condition indicates that if exhaustible resources are essential for production ($\alpha > 0$), positive output growth is not assured even when the level of R&D activity is strictly positive because resource scarcity has a negative impact on output growth. Solving $\gamma_N^* > \alpha(\epsilon-1)(\gamma_\tau+\rho)$ using (25), a positive output growth is possible if and only if

$$\varphi L > (\epsilon-1)\left\{\alpha\left[1+(1-\alpha)(\epsilon-1)\right]\gamma_\tau + [1+\alpha(1-\alpha)(\epsilon-1)]\rho\right\}. \tag{30}$$

Since the right-hand side of (30) increases with γ_τ, the higher resource tax growth rate γ_τ shrinks the parameter regions where a positive output growth rate is possible.

3.2 Resource taxation and growth

This subsection examines how the resource tax growth rate γ_τ and the resource tax level τ_0 affect the resource extraction rate γ_H^*, the interest rate r^*, the product variety growth rate γ_N^*, and the output growth rate γ_Y^*. By the effect of the resource tax growth rate γ_τ, we mean that the government sets a higher or lower resource tax growth rate while keeping the initial tax level τ_0 unchanged. Analogously, by the effect of the resource tax level τ_0, we mean that the government sets a higher or lower initial resource tax level while keeping the growth rate γ_τ unchanged.

Let us first examine the effects of the resource tax growth rate γ_τ on γ_H^*, r^*, γ_N^*, and γ_Y^*. From equations (25) to (29), we obtain the following comparative statics results.[6]

[6] Substituting (25) into (26) and (28) yields $\gamma_H^* = \frac{\frac{\sigma-1}{\epsilon-1}\varphi L + \frac{\sigma+(1-\alpha)\left[(\epsilon-1)(1-\alpha+\alpha\sigma)+\alpha(\sigma-1)^2\right]}{(1-\alpha+\alpha\sigma)}\gamma_\tau + [1+(1-\alpha)(\epsilon-1)]\rho}{\sigma+(1-\alpha)(1-\alpha+\alpha\sigma)}$ and $\gamma_Y^* = \frac{\frac{\varphi L}{(\epsilon-1)} + [1+(1-\alpha)(\epsilon-1)]\alpha\gamma_\tau - [1+\alpha(1-\alpha)(\epsilon-1)\rho]}{\sigma+(1-\alpha)(\epsilon-1)(1-\alpha+\alpha\sigma)}$.

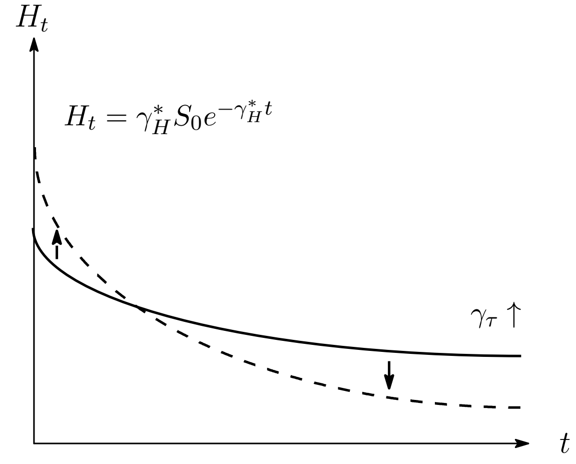

Figure 2: The dynamic path of H_t

Proposition 2 *The resource tax growth rate γ_τ affects the resource extraction rate γ_H^*, interest rate r^*, product variety growth rate γ_N^*, and output growth rate γ_Y^* as follows:*

$$\frac{\partial \gamma_H^*}{\partial \gamma_\tau} = \frac{\sigma + (1-\alpha)\left[(\epsilon - 1)(1-\alpha+\alpha\sigma) + \alpha(\sigma-1)^2\right]}{\left[\sigma + (1-\alpha)(1-\alpha+\alpha\sigma)\right](1-\alpha+\alpha\sigma)} > 0, \tag{31}$$

$$\frac{\partial r^*}{\partial \gamma_\tau} = -\frac{\sigma\alpha\left[1 + (1-\alpha)(\epsilon-1)\right]}{\sigma + (1-\alpha)(\epsilon-1)(1-\alpha+\alpha\sigma)} < 0. \tag{32}$$

$$\frac{\partial \gamma_N^*}{\partial \gamma_\tau} = \frac{(1-\alpha)(\epsilon-1)\alpha(\sigma-1)}{\sigma + (1-\alpha)(\epsilon-1)(1-\alpha+\alpha\sigma)}, \begin{cases} \geq 0, \text{ for } \sigma \geq 1, \\ < 0, \text{ for } \sigma < 1. \end{cases} \tag{33}$$

$$\frac{\partial \gamma_Y^*}{\partial \gamma_\tau} = -\frac{\alpha\left[1 + (1-\alpha)(\epsilon-1)\right]}{\sigma + (1-\alpha)(\epsilon-1)(1-\alpha+\alpha\sigma)} < 0, \tag{34}$$

where the relation $\partial\gamma_N^*/\partial\gamma_\tau = 0$ holds when $\sigma = 1$.

Equations (31) and (32) show that a higher resource tax growth rate γ_τ increases the resource extraction rate γ_H^* but decreases the interest rate r^*. From (27), as shown in Figure 2, a higher resource tax growth rate γ_τ increases resource demand in the intermediate goods sector during the earlier period and decreases it during the later period. When the resource tax growth rate γ_τ is raised, the resource price $\tau_t p_{H,t}$ faced by intermediate goods producers will be higher in the future, so intermediate goods producers demand more resources immediately and less in the future. As a result, the producer price of resource $p_{H,t}$ faced by resource firms will be lower in the future, so resource firms will supply more resources immediately and less in the future. Consequently, the equilibrium rate of resource extraction γ_H^* increases as shown in (31). Recall from the Hotelling rule in (3) that the growth rate of the producer price of the resource is equal to the interest rate (i.e., $\gamma_{p_H}^* \equiv \dot{p}_{H,t}/p_{H,t} = r^*$). When the resource tax growth rate γ_τ is raised, the rate of increase in the producer price of the resource $p_{H,t}$ declines, as does the equilibrium rate of interest r^*, as shown in (32).

Equation (33) shows that when $\sigma > 1$, a higher resource tax growth rate γ_τ stimulates R&D activity and increases the product variety growth rate γ_N^*, whereas the opposite prediction holds when $\sigma < 1$. As suggested by (22), a higher patent value $1/V^*$ results in a higher product variety growth rate γ_N^*. Here, recall that V^* represents the inverse measure of the patent value adjusted by the market size. Using the arbitrage condition in (13) and the Euler equation in (16), as shown in Appendix C, the equilibrium patent value $1/V^*$ is expressed as

$$\frac{1}{V^*} = \frac{1}{\epsilon\left(r^* - \gamma_Y^* + \gamma_N^*\right)} = \frac{1}{\epsilon\left(\frac{\sigma-1}{\sigma}r^* + \frac{\rho}{\sigma} + \gamma_N^*\right)}.$$

where we have used the steady state Euler equation $\gamma_Y^* = (1/\sigma)(r^* - \rho)$ to derive the second equality. The above equation shows that, ceteris paribus, a higher interest rate r^* negatively affects the patent value $1/V^*$ when $\sigma > 1$ but positively affects $1/V^*$ when $\sigma < 1$. A higher interest rate r^* negatively affects the patent value $1/V^*$ through an increase in the discount rate but positively affects $1/V^*$ through an increase in the growth rate of the size of the intermediate goods market. Whether the former negative effect of r^* on $1/V^*$ outweighs the latter positive effect depends on the value of σ. If $\sigma > 1$ ($\sigma < 1$), the former negative effect of r^* on $1/V^*$ outweighs (is outweighed by) the latter positive effect. From (32), we see that a higher resource tax growth rate γ_τ decreases the interest rate r^*. Therefore, when $\sigma > 1$ ($\sigma < 1$), a higher resource tax growth rate γ_τ positively (negatively) affects the patent value $1/V^*$ and increases (decreases) the product variety growth rate γ_N^*.

Equation (34) shows that a higher resource tax growth rate γ_τ decreases the output growth rate γ_Y^*. On the one hand, when $\sigma > 1$, from (28), we know that the resource tax growth rate γ_τ has two opposing effects on output growth γ_Y^*. An increase in γ_τ stimulates R&D activities, thereby affecting output growth γ_Y^* positively through a rise in the variety growth rate γ_N^*. However, an increase in γ_τ increases the resource extraction rate γ_H^*, which depresses output growth γ_Y^*. In the present model, since the latter negative effect always outweighs the former positive effect, a higher resource tax growth rate γ_τ decreases the output growth rate γ_Y^*. On the other hand, when $\sigma < 1$, an increase in γ_τ negatively affects output growth γ_Y^* not only through an increase in the resource extraction rate but also through a decline in the variety growth rate γ_N^*. Therefore, regardless of the value of σ, an increase in γ_τ decreases the output growth rate γ_Y^* as shown in (34).

Let us next examine the effects of the resource tax level τ_0 on γ_H^*, r^*, γ_N^*, and γ_Y^*. Equations (25) to (29) show that for a given resource tax growth rate γ_τ, changes in the resource tax level τ_0 have no effect on γ_H^*, r^*, γ_N^*, and γ_Y^*. The higher resource tax level τ_0 permanently lowers resource demand by a constant factor, but the intertemporal arbitrage of resource firms remains unaffected. As a result, the producer price of the resource decreases, leaving the price that intermediates producers have to pay unchanged. Thus, the resource tax level τ_0 affects neither the allocation of resources and labour nor the rate of resource extraction. From (17), a change in the tax level τ_0 only changes the size of government transfers to households through resource tax revenues.

These findings of the relationship between resource taxation and economic growth are in line with existing R&D-based growth models with exhaustible resources (e.g., Grimaund and Rouge, 2004 2014; Daubanes and Grimaund, 2010; Pittel and Bretschger, 2010). The novelty of this paper is its detailed examination of the impact of resource taxation on growth and inequality in a model that allows for heterogeneous households with different assets, focusing on the empirically relevant case where the intertemporal substitution is sufficiently small to satisfy $\sigma \geq 1$ (e.g., Guvenen 2006).

4 Resource taxation and consumption inequality

In this section, we explore the effects of resource taxation on consumption inequality. Section 4-1 shows that the consumption distribution is stationary and is determined by the equilibrium outcome of the lifetime wealth distribution among heterogeneous households. Section 4-2 explains the determination of the size of the resource tax and how resource tax revenues are distributed to households. Section 4-3 examines how the resource tax growth rate, the size of the resource tax, and the way in which tax revenues are redistributed to households affect consumption inequality.

4.1 Lifetime wealth and consumption distribution

At time 0, the initial resource share and initial patent share of household h are exogenously given by $\theta_S(h)$ and $\theta_N(h)$ (i.e., $\theta_S(h) \equiv S_0(h)/S_0$, $\theta_N(h) \equiv N_0(h)/N_0$), which have a joint distribution function f with $\mu_S = 1$, $\mu_N = 1$, $\sigma_N > 0$, $\sigma_S > 0$, and $\sigma_{SN} \geq 0$. Here, μ_j denotes the mean of $\theta_j(h)$ for $j = S, N$; σ_j denotes the standard deviation of $\theta_j(h)$ for $j = S, N$; and σ_{SN} denotes the covariance of $\theta_S(h)$ and $\theta_N(h)$. We assume that the initial resource share $\theta_S(h)$ and initial patent share $\theta_N(h)$ of household h are positively correlated such that their covariance satisfies $\sigma_{SN} \geq 0$.

We define the household wealth $W_t(h)$ at time t as the sum of the present value of the wage income $\{w_s L\}_{s=t}^{\infty}$ (i.e., human wealth), the government's lump-sum tax/transfer $\{T_s(h)\}_{s=t}^{\infty}$, and the private asset $A_t(h)$ as follows:

$$W_t(h) \equiv \int_t^{\infty} [w_s L + T_s(h)]\, e^{-\int_t^s r_u du} ds + A_t(h), \tag{35}$$

where $W_0(h)$ represents the lifetime wealth of household h. Using the definition of $W_t(h)$ in (35), the household budget constraint of (15) is rewritten as $\int_t^{\infty} C_s(h) e^{-\int_t^s r_u du} ds = W_t(h)$. Thus, the household wealth $W_t(h)$ evolves according to

$$\dot{W}_t(h) = r_t W_t(h) - C_t(h). \tag{36}$$

Aggregating (36) across all households yields the following aggregate wealth equation:

$$\dot{W}_t = r_t W_t - C_t, \tag{37}$$

where $W_t \equiv \int_0^1 W_t(h) dh$. Combining (36) and (37) yields the law of motion for the wealth share $\theta_{W,t}(h) \equiv W_t(h)/W_t$ given by

$$\frac{\dot{\theta}_{W,t}(h)}{\theta_{W,t}(h)} = \frac{\dot{W}_t(h)}{W_t(h)} - \frac{\dot{W}_t}{W_t} = \frac{C_t}{W_t} - \frac{C_t(h)}{W_t(h)}, \tag{38}$$

which can be re-expressed as

$$\dot{\theta}_{W,t}(h) = \frac{C_t}{W_t} \left[\theta_{W,t}(h) - \theta_{C,t}(h)\right], \tag{39}$$

where $\theta_{C,t}(h) \equiv C_t(h)/C_t$. From (16), $\dot{C}_t(h)/C_t(h) = \dot{C}_t/C_t = (1/\sigma)(r_t - \rho)$, which implies that the consumption share $\theta_{C,t}(h)$ is stationary and satisfies $\dot{\theta}_{C,t}(h)/\theta_{C,t}(h) = 0$ and $\theta_{C,t}(h) = \theta_{C,0}(h)$ for all $t \geq 0$. Appendix C shows that the aggregate economy is always on the balanced growth path along which C_t/W_t is stationary and satisfies

$C_t/W_t = r^* - \gamma_Y^* > 0$ for all $t \geq 0$. Therefore, equation (39) is a one-dimensional differential equation that describes the potential evolution of $\theta_{W,t}(h)$ given an initial $\theta_{W,0}(h)$. Since the coefficient of $\theta_{W,t}(h)$ in (39) is positive and $\theta_{W,t}(h)$ is the predetermined variable, to achieve the stability of $\theta_{W,t}(h)$, $\dot{\theta}_{W,t}(h) = 0$ must hold for all $t \geq 0$. This stability condition can be achieved if and only if $\theta_{W,t}(h)$ jumps to a stationary level at $t = 0$. Therefore, the wealth share $\theta_{W,t}(h)$ is also stationary and satisfies $\theta_{W,t}(h) = \theta_{W,0}(h)$ for all $t \geq 0$. Moreover, from (39), $\dot{\theta}_{W,t}(h) = 0$ for all $t \geq 0$ implies that $\theta_{C,t}(h) = \theta_{W,t}(h)$ for all $t \geq 0$. The consumption share $\theta_{C,t}(h)$ equals the wealth share $\theta_{W,t}(h)$ at all times. Summarizing these results, we obtain the following proposition.

Proposition 3 *For every household $h \in [0, 1]$, the following statements hold.*

1. *The share of household h's wealth $\theta_{W,t}(h)$ is constant over time such that $\theta_{W,t}(h) = \theta_{W,0}(h)$ for all $t \geq 0$.*

2. *The share of household h's consumption $\theta_{C,t}(h)$ is equal to the share of household h's wealth $\theta_{W,t}(h)$ such that $\theta_{C,t}(h) = \theta_{W,t}(h)$ for all $t \geq 0$.*

Proposition 3 states that as an equilibrium outcome, the share of household h's consumption $\theta_{C,t}(h)$ at time t is equal to the share of household h's wealth $\theta_{W,0}(h)$ at time 0. The consumption distribution is always equal to the household wealth distribution, which remains unchanged over time. The definition of $W_0(h)$ in (35) implies that the initial household wealth distribution is affected by initial resource prices and initial patent prices, which are endogenously determined through intertemporal arbitrage asset transactions that households undertake to smooth consumption over time. As a result, resource taxes affect the initial household wealth distribution through their impact on initial resource prices and patent prices. Moreover, the initial household wealth distribution is affected by the size of the resource tax and the way in which tax revenues are redistributed to households. To consider this issue, the next subsection describes how the government distributes resource tax revenues to heterogeneous households.

4.2 Distribution to households

Let us first explain how resource tax revenues are distributed to households. The government determines the level of lump-sum tax/transfer to household h according to the following policy rule:

$$T_t(h) = [\lambda + (1 - \lambda)\, \theta_S(h)]\, T_t, \tag{40}$$

where $\lambda \in [0, 1]$. The parameter λ represents the degree of redistribution of government transfers. A larger value of λ indicates a greater degree of redistribution of government transfers. If $\lambda = 1$, the government distributes resource tax revenues T_t at time t equally among households (i.e., $T_t(h) = T_t$). In this case, since rich households possess more resources than poor households, these policies indicate a net income transfer from the rich to the poor. On the other hand, if $\lambda = 0$, the government distributes resource tax revenues T_t at time t according to households' initial resource share $\theta_S(h)$ (i.e., $T_t(h) = \theta_S(h) T_t$). In this case, since government transfers do not involve income transfers from the rich to the poor, these policies have no redistributive role.

Next, let us describe the determination of the size of the resource tax. From (17) and Appendix D, the present value of resource tax revenues at time 0 is given by

$$TR_0 \equiv \int_0^{\infty} T_s e^{-\int_t^s r_u du} ds = \left(\frac{r^* - \gamma_Y^* + \gamma_\tau}{r^* - \gamma_Y^*} \tau_0 - 1 \right) p_{H,0} S_0, \tag{41}$$

which implies that the tax base for resource taxation is the initial resource value $p_{H,0}S_0$. The term $[(r^* - \gamma_Y^* + \gamma_\tau)/(r^* - \gamma_Y^*)]\tau_0 - 1$ represents the effective tax rate on the initial resource value $p_{H,0}S_0$, which is determined by the initial resource tax level τ_0 and the resource tax growth rate γ_τ.[7] In the following analysis, we assume that the government maintains the effective tax rate on $p_{H,0}S_0$ at a constant value of $\psi \in [0, 1)$ and adjusts the value of τ_0 to satisfy the following condition.[8]

$$\psi = \left(\frac{r^* - \gamma_Y^* + \gamma_\tau}{r^* - \gamma_Y^*} \tau_0 - 1 \right). \tag{42}$$

Under this fiscal rule, since $TR_0 = \psi p_{H,0}S_0$, resource tax revenues are always given as a fixed $\psi \in [0, 1)$ ratio of the initial resource value. Given that all resource tax revenues are distributed to households, the parameter ψ represents the magnitude of government transfers to households. A larger value of ψ indicates a greater magnitude of government transfers to households.

4.3 Consumption inequality

This subsection examines how the resource tax growth rate γ_τ, the size of the resource tax ψ, and the degree of redistribution λ of government transfers affect consumption inequality.

As stated in Proposition 3, the share of household h's consumption $\theta_{C,t}(h)$ at time t is equal to the share of household h's wealth $\theta_{W,0}(h)$ at time 0. By substituting (41) and (42) into (35), household h's wealth at time 0 (the lifetime wealth) is rewritten as

$$W_0(h) = \left[\int_0^\infty w_s L e^{-\int_0^s r_u du} ds + \lambda TR_0 \right] + \left[v_0^S + (1 - \lambda) TR_0 \right] \theta_S(h) + v_0 N_0 \theta_N(h). \tag{43}$$

The right-hand side of (43) is decomposed into three terms. The first term represents the sum of the present value of household h's wage income (human wealth) and the present value of the government transfers that household h receives regardless of its initial resource holdings. Here, recall that the parameter λ represents the degree of redistribution of government transfers. The second term represents the sum of the value of household h's initial resources and the present value of the government transfers that household h receives in proportion to its initial resource holdings. The third term represents the value of household h's initial patents. Since there is no heterogeneity in labour income, the first term is the same for every household $h \in [0, 1]$. However, due to heterogeneity in initial asset holdings, the second and third terms have different values for each household h.

Dividing (43) by total wealth W_0, as shown in Appendix D, gives the share of household h's wealth $\theta_{W,0}(h)$ at time 0 and the share of household h's consumption $\theta_{C,t}(h)$ at time t as a weighted average of 1, $\theta_S(h)$, and $\theta_N(h)$:

$$\theta_{W,0}(h) = \theta_{C,t}(h) = (1 - q_S - q_N) + q_S \theta_S(h) + q_N \theta_N(h), \tag{44}$$

where $q_S \equiv \frac{\alpha(\epsilon-1)}{\epsilon}(1 - \frac{\psi}{1+\psi}\lambda)$ and $q_N \equiv \frac{1}{\epsilon} \frac{r^* - \gamma_Y^*}{r^* - \gamma_Y^* + \gamma_N^*}$. The weights of 1, $\theta_S(h)$, and $\theta_N(h)$ are given by $1 - q_S - q_N$, q_S, and q_N, which represent the relative importance of the first,

[7] If the resource tax growth rate γ_τ is zero (i.e., $\tau_t = \tau_0$), the effective tax rate on $p_{H,0}S_0$ is given by $\tau_0 - 1$.

[8] Under this fiscal rule, this paper focuses on the effect of the resource tax growth rate γ_τ on consumption inequality through channels other than changes in the size of government transfers. The results of the analysis without imposing this fiscal rule are briefly discussed in Chapter 6.

second, and third terms in (43) for determining the value of $\theta_{C,t}(h)$ in (44). Equation (44) implies that the distribution of consumption share $\theta_{C,t}(h)$ at time t has a mean of one and a standard deviation of

$$\sigma_C \equiv \sqrt{\int_0^1 \left[\theta_C(h) - 1\right]^2 dh} = \sqrt{q_S^2\sigma_S^2 + q_N^2\sigma_N^2 + 2q_S q_N \sigma_{SN}}. \tag{45}$$

We measure consumption inequality by the standard deviation of consumption share σ_C, which is equivalent to the coefficient of variation of consumption. Under the assumption that $\sigma_{SN} \geq 0$, because $\partial\sigma_C^2/\partial q_S > 0$ and $\partial\sigma_C^2/\partial q_N > 0$, the larger weights q_S and q_N of $\theta_S(h)$ and $\theta_N(h)$ in (44) positively affect consumption inequality σ_C because initial asset heterogeneity plays a more important role in determining the value of $\theta_{C,t}(h)$. Furthermore, if the correlation coefficient between $\theta_S(h)$ and $\theta_N(h)$ is 1, the relation $\sigma_{SN} = \sigma_S\sigma_N$ holds, so the standard deviation of consumption share σ_C in (45) is rewritten as

$$\sigma_C = q_S\sigma_S + q_N\sigma_N,$$

which is expressed as a simple weighted sum of the standard deviations of the initial resource share σ_S and initial patent share σ_N.

From (45), by differentiating σ_C with respect to γ_τ, ψ and λ using (25), (28) and (29), we obtain

$$\frac{\partial\sigma_C}{\partial\gamma_\tau} = \frac{1}{2\sigma_C}\underbrace{\frac{\partial\sigma_C^2}{\partial q_N}}_{(>0)}\frac{\partial q_N}{\partial\gamma_\tau}\begin{cases}\leq 0, & \text{for } \sigma \geq 1,\\ > 0, & \text{for } \sigma < 1.\end{cases} \tag{46}$$

$$\frac{\partial\sigma_C}{\partial\psi} = \frac{1}{2\sigma_C}\underbrace{\frac{\partial\sigma_C^2}{\partial q_S}}_{(>0)}\frac{\partial q_S}{\partial\psi} < 0, \tag{47}$$

$$\frac{\partial\sigma_C}{\partial\lambda} = \frac{1}{2\sigma_C}\underbrace{\frac{\partial\sigma_C^2}{\partial q_S}}_{(>0)}\frac{\partial q_S}{\partial\lambda} < 0, \tag{48}$$

where

$$\frac{\partial q_N}{\partial\gamma_\tau} = -\frac{\alpha(\sigma-1)\left\{\left[1+(1-\alpha)(\epsilon-1)\right]\gamma_N^* + (1-\alpha)(\epsilon-1)(r^*-\gamma_Y^*)\right\}}{\epsilon\left[\sigma+(1-\alpha)(\epsilon-1)(1-\alpha+\alpha\sigma)\right](r^*-\gamma_Y^*+\gamma_N^*)^2}\begin{cases}\leq 0, & \text{for } \sigma \geq 1,\\ > 0, & \text{for } \sigma < 1,\end{cases} \tag{49}$$

$$\frac{\partial q_S}{\partial\psi} = -\alpha\frac{\epsilon-1}{\epsilon}\frac{\lambda}{(1+\psi)^2} < 0, \tag{50}$$

$$\frac{\partial q_S}{\partial\lambda} = -\alpha\frac{\epsilon-1}{\epsilon}\frac{\psi}{1+\psi} < 0. \tag{51}$$

The derivation of (49) is shown in Appendix D.

Equation (46) shows that the sign of $\partial\sigma_C/\partial\gamma_\tau$ depends on the sign of $\partial q_N/\partial\gamma_\tau$ in (49). When $\sigma > 1$ ($\sigma < 1$), a higher resource tax growth rate γ_τ decreases (increases) the value of the weight parameter q_N given to $\theta_N(h)$ in (44), which reduces (increases) consumption inequality σ_C as shown in (46). Intuitively, when $\sigma > 1$ ($\sigma < 1$), the higher resource tax growth rate closes (widens) the gap between the real interest rate and the economic growth rate (see (A.21)), which reduces the relative importance of heterogeneity in initial patent holdings for determining the value of $\theta_{C,t}(h)$ in (44), thus reducing consumption inequality. As Piketty (2014) argues, the gap between the real interest rate and the economic growth rate crucially affects the distribution of wealth and thus consumption inequality because inherited wealth grows faster than labour income, resulting in a highly concentrated distribution of wealth. As a result, when $\sigma > 1$ ($\sigma < 1$), a higher resource tax growth rate has a negative effect on consumption inequality by closing (widening) the gap between the real interest rate and the economic growth rate and mitigating the impact of heterogeneity in initial patent holdings on consumption inequality. Furthermore, when $\sigma > 1$ ($\sigma < 1$), a higher resource tax growth rate has an additional negative (positive) effect on consumption inequality by encouraging (discouraging) R&D activities and enhancing (slowing) the growth rate of real wages. When $\sigma > 1$ ($\sigma < 1$), a higher resource tax growth rate has competing effects on R&D activities. On the one hand, it stifles (enhances) economic growth, retards (promotes) growth in the size of the market for new intermediate inputs inventions, and discourages (stimulates) R&D activities. On the other hand, it decreases (increases) the real interest rate, which raises (decreases) the present value of new inventions by decreasing (increasing) the discount rate and encourages (discourages) R&D activities. When $\sigma > 1$ ($\sigma < 1$), because the latter positive (negative) effect always dominates the former negative (positive) effect, a higher resource tax growth rate encourages (discourages) R&D activities, enhances (suppresses) real wage growth, and thus negatively (positively) affects consumption inequality.

Equations (47) and (48) also show that the signs of $\partial\sigma_C/\partial\psi$ and $\partial\sigma_C/\partial\lambda$ depend on the sign of $\partial q_S/\partial\psi$ in (50) and $\partial q_S/\partial\lambda$ in (51), respectively. Both a larger size of government transfers ψ and a greater degree of redistribution λ of government transfers decrease the value of the weight parameter q_S given to $\theta_S(h)$ in (44), which reduces consumption inequality σ_C as shown in (47) and (48). Intuitively, these policies increase the size of government redistribution and reduce the relative importance of heterogeneity in initial resource endowments for determining the value of $\theta_{C,t}(h)$ in (44), thus reducing consumption inequality.

Summarizing these results, we obtain the following proposition.

Proposition 4 *Under the resource taxation policies defined in Section 4-2, the following statements hold.*

1. *The degree of consumption inequality σ_C decreases (increases) with the resource tax growth rate γ_τ if and only if the elasticity of intertemporal substitution $1/\sigma$ is less (greater) than unity.*

2. *The degree of consumption inequality σ_C decreases with the size of resource tax ψ and the degree of redistribution λ in government transfers to households.*

Before closing this subsection, to prepare for the numerical analysis, we sort households in ascending order of consumption and define the Gini coefficient of consumption at time t as

$$\sigma_C^G \equiv 1 - 2\int_0^1 \mathcal{L}_C(h)dh \tag{52}$$

where the Lorenz curve of consumption $\mathcal{L}_C(h)$ inside the integral is given by $\mathcal{L}_C(h) \equiv \int_0^h \theta_{C,t}(z)dz$. In the following simulation analysis, we focus on the Gini coefficient due to limited data availability for other inequality measures. In addition, because it is difficult to obtain detailed data on the relationship between initial patent holdings and resource

Table 1: Benchmark Parameter Values

Parameter	Description	Value
ρ	Discount rate	0.04
L	Labor size	1
σ	Intertemporal substitution $1/\sigma$	3
ϵ	Elasticities of substitution	4.33333
α	Resource intensity	0.15
φ	R&D efficiency	0.63555
γ_τ	The resource tax growth rate	0
ψ	Effective tax rate on the initial resource value	0.24408
λ	The degree of redistribution through government transfers	0
σ_S^G	Gini coefficient of the initial resource	0.83
σ_N^G	Gini coefficient of the initial patent	0.83

holdings, we adopt the slightly limiting assumption that the order of households with respect to initial resource holdings and those with respect to initial patent holdings are the same. Under this assumption, the Lorenz curves of the initial resource $\mathcal{L}_S(h)$ and the initial patent $\mathcal{L}_N(h)$ are defined by $\mathcal{L}_S(h) \equiv \int_0^h \theta_S(z)dz$ and $\mathcal{L}_N(h) \equiv \int_0^h \theta_N(z)dz$, respectively. Therefore, the Gini coefficients of the initial resource σ_S^G and the initial patent σ_N^G are given by $\sigma_S^G \equiv 1-2\int_0^1 \mathcal{L}_S(h)dh$ and $\sigma_N^G \equiv 1-2\int_0^1 \mathcal{L}_N(h)dh$, respectively. Substituting (44) into $\mathcal{L}_C(h) \equiv \int_0^h \theta_{C,t}(z)dz$, we obtain $\mathcal{L}_C(h) = (1-q_S-q_N)\,h + q_S\mathcal{L}_S(h) + q_N\mathcal{L}_N(h)$. Thus, by substituting this equation into (52), the Gini coefficient of consumption at time t in (52) is rewritten as

$$\sigma_C^G = q_S\sigma_S^G + q_N\sigma_N^G, \tag{53}$$

which is expressed as a simple weighted sum of the Gini coefficients of the initial resource σ_S^G and the initial patent σ_N^G. This property of the Gini coefficient of consumption σ_C^G in (53) is similar to the property of the standard deviation of consumption in (45) at which the correlation coefficient between $\theta_S(h)$ and $\theta_N(h)$ is 1 (i.e., $\sigma_{SN} = \sigma_S\sigma_N$). The following simulation analysis focuses on this limited case due to data availability.

5 Quantitative analysis

In this section, to obtain further insights with respect to the effects of resource taxation on output growth and consumption inequality, we resort to the numerical simulations of our model. The main objective of the following numerical exercises is not to calibrate our simple model to actual data but to supplement the qualitative results of our theoretical model. Although we carefully chose the parameter values, the quantitative results obtained in our paper should be interpreted with caution.

5.1 Model parameterization

Table 1 provides a summary of the model parameters. The discount rate is fixed to $\rho = 0.04$ following Chu and Peretto (2019), and the labour size is normalized to $L = 1$. As the inverse measure of the intertemporal substitution, we set a conservative value of

$\sigma = 3$, which implies an intertemporal substitution elasticity of 0.33, within the usual range in the business cycle literature. In the final goods sector, we set the elasticity of substitution across intermediate varieties to $\epsilon = 4.33333$, yielding a price-cost markup of $\epsilon/(\epsilon - 1) = 1.3$, which is within the range of estimates presented by Britton et al. (2000) and Gali et al. (2007). In the intermediate sector, the resource intensity is set to $\alpha = 0.15$ following Suphaphiphat et al. (2015). In the R&D sector, we set the efficiency parameter for R&D to $\varphi = 0.63555$, targeting the benchmark growth rate of $\gamma_Y^* = 0.02$.

Although many countries have increased tax rates per unit of fossil fuel use and emission, revenues from environmentally related taxes, including energy and resource taxes, have remained relatively stable over the last two decades. For example, according to OECD (2024), the ratio of environmentally related tax revenues to GDP in OECD countries declined from 1.81% in 2000 to 1.5% in 2020, although these values vary considerably from country to country.[9] Based on these data and the fact that our model employs an ad valorem tax formulation, we set the benchmark resource tax growth rate to $\gamma_\tau = 0$ and vary it from -0.04 to 0.04. The effective tax rate on the initial resource value is set at $\psi = 0.24408$ so that the benchmark ratio of resource tax revenues to GDP in our model generates 2%, which is roughly consistent with the average ratio of environmentally related tax revenues to GDP for the G7 countries from 2000 to 2020. The derivation of the ratio of resource tax revenues to GDP in our model is explained in Appendix E. According to estimates by the World Bank (2019), only 3% of carbon revenues in OECD countries are allocated to direct transfers to households and businesses.[10] With reference to this estimate, we adopt a conservative approach by setting the benchmark value of the degree of redistribution of government transfers to $\lambda = 0$ and vary it from 0 to 1. The World Income Inequality Database (2023) shows that the Gini coefficient for net personal wealth in the US in 2000 is approximately 0.83. Based on this estimate, we set the benchmark values of the Gini coefficients for resources and patents to $\sigma_S^G = 0.83$ and $\sigma_N^G = 0.83$. We also perform several simulation analyses under various pairs of σ_S^G and σ_N^G designed so that the Gini coefficient of household assets at the benchmark is 0.83. The derivation of the Gini coefficient of household assets in our model is also explained in Appendix E.

5.2 The effects of resource taxation

Figures 3-a to 3-c show how the output growth rate γ_Y^* (Figure 3-a), resource extraction rate γ_H^* (Figure 3-b), and consumption inequality measured by the Gini coefficients σ_N^G defined in (53) (Figure 3-c) respond to changes in the resource tax growth rate γ_τ from -0.04 to $+0.04$ under different values of the degree of redistribution λ of government transfers. The solid lines show the results when $\lambda = 0$, while the dashed and dotted lines show the results when $\lambda = 0.5$ and $\lambda = 1$, respectively. The Gini coefficient of consumption in our benchmark (i.e., $\gamma_\tau = \lambda = 0$) is 0.1779, which is smaller than Krueger and Perri's (2006) empirical estimates of 0.23 to 0.26 for the US from1980 to 2004. This is

[9] According to OECD (2024), even in EU countries, the ratio of environmentally related tax revenues to GDP declined from 2.56% in 2000 to 2.24% in 2020. Taxation on fossil fuels and energy has complex structures. For example, raising the tax rate on fossil fuels is often offset by raising subsidies, leaving the effective tax rate unchanged. In addition, an increase in the tax rate on fossil fuels itself reduces the tax base, resulting in stagnant tax revenues. For a more detailed explanation of why environmentally related tax revenues remain stable, see, for example, EEA (2021).

[10] According to Figure 1 on page 7 of World Bank (2019), the majority of carbon revenues are allocated to environmental projects (42%). Other revenue allocations include general budget (38%), development-related (11%), reductions in other taxes (6%), and direct transfers to households and businesses (3%).

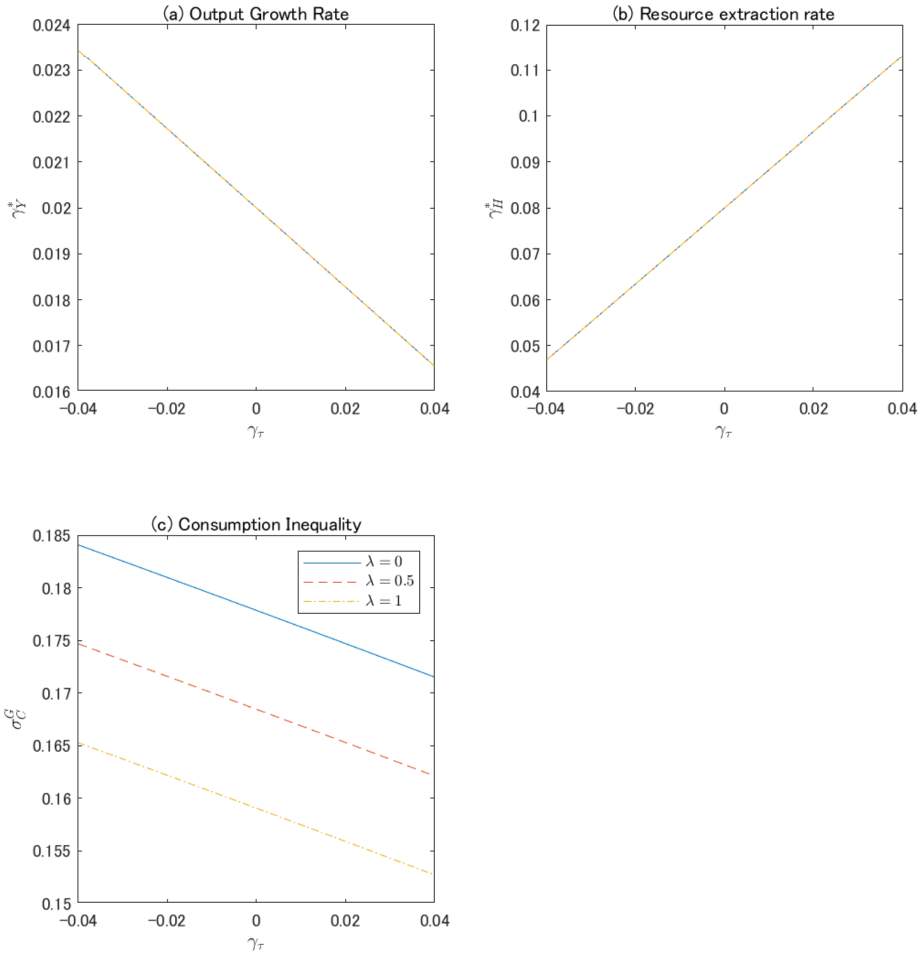

Figure 3: The effects of γ_τ on γ_Y^* γ_H^* and σ_C^G for $\lambda = 0, 0.5$ and 1, when $\sigma_S^G = \sigma_N^G = 0.8300$.

Table 2: The effects of γ_τ on γ_Y^*, q_S, q_N, and σ_C^G when $\lambda = 0$.

γ_τ	γ_Y^*	q_S	q_N	σ_C^G		
				(a) $\sigma_S^G < \sigma_N^G$ (0.6902, 0.9932)	(b) $\sigma_S^G = \sigma_N^G$ (0.8300,0.8300)	(c) $\sigma_S^G > \sigma_N^G$ (0.9957,0.6366)
0.04	1.6558%	0.1154	0.0913	0.1703	0.1715	0.1730
0.02	1.8279%	0.1154	0.0951	0.1741	0.1747	0.1754
0.00	2.0000%	0.1154	0.0989	0.1779	0.1779	0.1779
-0.02	2.1720%	0.1154	0.1027	0.1816	0.1810	0.1803
-0.04	2.3441%	0.1154	0.1064	0.1853	0.1841	0.1826

partly because our model ignores heterogeneity with respect to labour income. Since the intertemporal elasticity of substitution is sufficiently small to satisfy $\sigma > 1$ in our simulation, as shown in Figure 3, a lower resource tax growth rate γ_τ slows resource extraction γ_H^* (Figure 3-b) and promotes output growth γ_Y^* (Figure 3-a) but increases consumption inequality σ_C^G (Figure 3-c). These results are consistent with those obtained in Propositions 2 and 4. Figures 3-a to 3-c also show that for a given value of γ_τ, increasing the degree of redistribution λ of government transfers from 0 to 1 reduces consumption inequality σ_C^G (Figure 3-c), while the output growth rate γ_Y^* (Figure 3-a) and the resource extraction rate γ_H^* (Figure 3-b) remain unchanged. Here, recall that the initial tax level τ_0 does not affect either the output growth rate γ_Y^* or the resource extraction rate γ_H^*, as discussed in Section 3-2.

Table 2 shows how changes in the resource tax growth rate γ_τ affect the output growth rate γ_Y^*, the weight parameter q_S given to σ_S^G in (53), the weight parameter q_N given to σ_N^G, and consumption inequality σ_C^G. As already shown in Figure 3-(a), the output growth rate γ_Y^* increases as the growth rate of the resource tax γ_τ decreases from 0.04 to -0.04. For illustrative purposes, we consider three different pairs of σ_S^G and σ_N^G designed so that the Gini coefficient of household assets in the benchmark is 0.83. Consequently, in the benchmark (i.e., $\gamma_\tau = 0$), consumption inequality σ_C^G is adjusted to 0.1779 regardless of the pair of σ_S^G and σ_N^G. Column 5 of Table 2 shows the results for (a) $\sigma_S^G < \sigma_N^G$, while columns 6 and 7 show the results for (b) $\sigma_S^G = \sigma_N^G$ and (c) $\sigma_S^G > \sigma_N^G$, respectively. Since the intertemporal elasticity of substitution is sufficiently small to satisfy $\sigma > 1$ in our simulation, as shown in Table 2, the lower resource tax growth rate γ_τ increases the value of the weight parameter q_N given to σ_N^G in (53), which increases consumption inequality σ_C^G regardless of the pair of σ_S^G and σ_N^G. These results are consistent with those obtained in (48). Since this increase in consumption inequality σ_C^G is caused by an increase in the weight parameter q_N given to σ_N^G, the increase in consumption inequality is largest for (a) $\sigma_S^G < \sigma_N^G$, as shown in Table 2. For example, when $\gamma_\tau = 0.04$, the consumption inequality in case (a) is smaller than those in cases (b) and (c), but as γ_τ decreases and $\gamma_\tau = -0.04$, the consumption inequality in case (a) exceeds those in cases (b) and (c).

Table 3 shows how changes in the degree of redistribution λ of government transfers affect the output growth rate γ_Y^*, the weight parameter q_S given to σ_S^G in (53), the weight parameter q_N given to σ_N^G, and consumption inequality σ_C^G. As already shown in Figure 3-(a), the output growth rate γ_Y^* remains unchanged even if the degree of redistribution λ of government transfers increases from 0 to 1. As in Table 2, Column 5 of Table 3 shows the results for (a) $\sigma_S^G < \sigma_N^G$, while columns 6 and 7 show the results for (b) $\sigma_S^G = \sigma_N^G$ and

Table 3: The effects of λ on γ_Y^*, q_S, q_N, and σ_C^G when $\gamma_\tau = 0$.

λ	γ_Y^*	q_S	q_N	σ_C^G		
				(a) $\sigma_S^G < \sigma_N^G$ (0.6902, 0.9932)	(b) $\sigma_S^G = \sigma_N^G$ (0.8300,0.8300)	(c) $\sigma_S^G > \sigma_N^G$ (0.9957,0.6366)
1.00	2.0000%	0.0927	0.0989	0.1622	0.1591	0.1553
0,75	2.0000%	0.0984	0.0989	0.1661	0.1638	0.1610
0.50	2.0000%	0.1041	0.0989	0.1700	0.1685	0.1666
0.25	2.0000%	0.1097	0.0989	0.1740	0.1732	0.1722
0.00	2.0000%	0.1154	0.0989	0.1779	0.1779	0.1779

(c) $\sigma_S^G > \sigma_N^G$, respectively. In the benchmark (i.e., $\lambda = 0$), the consumption inequality σ_C^G is adjusted to 0.1779 regardless of the pair of σ_S^G and σ_N^G. As shown in Table 3, a higher degree of redistribution λ of government transfers decreases the value of the weight parameter q_S given to σ_S^G in (53), which decreases consumption inequality σ_C^G regardless of the pair of σ_S^G and σ_N^G. Since this decrease in consumption inequality is caused by a decrease in q_S, the decrease in consumption inequality is largest for (c) $\sigma_S^G > \sigma_N^G$. Indeed, as the value of λ increases from 0 to 1, consumption inequality decreases from 0.1779 to 0.1553 in case (c) but only decreases from 0.1779 to 0.1622 in case (a) and from 0.1779 to 0.1591 in case (b).

Figure 4 depicts the degree of redistribution λ of government transfers required to achieve the same level of consumption inequality as in the benchmark case (i.e., $\gamma_\tau = \lambda = 0$). The solid line shows the result for (a) $\sigma_S^G < \sigma_N^G$, while the dashed and the dotted lines show the results for (b) $\sigma_S^G = \sigma_N^G$ and (c) $\sigma_S^G > \sigma_N^G$, respectively. If resource tax policies are to promote economic growth without exacerbating consumption inequality, the degree of redistribution λ of government transfers must increase as the growth rate of the resource tax γ_τ decreases from 0 to -0.04, as shown in Figure 4. Table 2 shows that the increase in consumption inequality associated with a decrease in γ_τ is largest for (a) $\sigma_S^G < \sigma_N^G$. Therefore, as shown in Figure 4, the degree of redistribution λ needed to prevent consumption inequality from worsening is also largest for (a) $\sigma_S^G < \sigma_N^G$.

6 Discussion

To clarify our main arguments on the effects of resource taxation on consumption inequality, we employ an analytically tractable R&D-based growth model with some restrictive specifications. Although these specifications enable us to obtain intuitive analytical results regarding the effect of resource taxation on consumption inequality, some are overly restrictive from both empirical and theoretical perspectives. Therefore, the application of our simple framework to assess the likely impact of policy reform is obviously limited. Here, we note several limitations of our specifications and discuss the robustness of our results and directions for future research.

First, for the clarity of our main arguments, we assume that the government maintains the effective tax rate on the initial resource value $p_{H,0}S_0$ at a constant value of $\psi \in [0, 1)$ and adjusts the value of τ_0 to satisfy (42). To check the robustness of our main theoretical results, Appendix F examines the alternative fiscal rule in which the initial tax level τ_0 is a fixed constant. Under this alternative fiscal rule, as shown in Appendix F, for $\sigma \geq 1$,

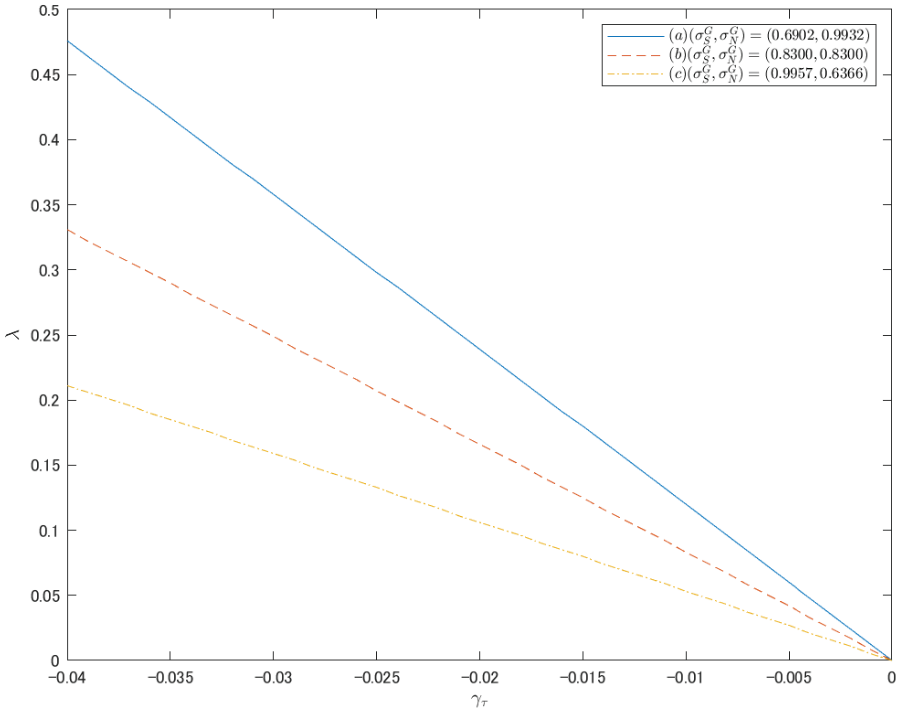

Figure 4: Degree of redistribution required to achieve the same level of consumption inequality as for the benchmark case $\lambda = 0$ and $\gamma_\tau = 0$.

a higher resource tax growth rate γ_τ increases the size of transfers from the government to households, leading to an increase in the size of the government redistributive policy. Consequently, when $\sigma \geq 1$, a higher resource tax growth rate γ_τ reduces consumption inequality σ_C not only through a lower value of the weight parameter given to $\theta_N(h)$ but also through a lower value of the weight parameter given to $\theta_S(h)$. Although a new channel is added in which the resource tax growth rate affects consumption inequality through changes in the size of government transfers, the qualitative implication of the resource tax growth rate γ_τ for consumption inequality σ_C remains unchanged. Our main theoretical results are robust under this alternative fiscal rule.

Second, to avoid unnecessary complications and to focus on the positive aspects of the resource tax policy, this paper does not explicitly model the negative externalities associated with the use of non-renewable resources. However, explicit consideration of a polluting non-renewable resource provides a rationale for taxing resource use. In particular, the model in this paper assumes a constant effective tax rate $\psi \in [0, 1)$ on the initial resource value $p_{H,0}S_0$, and thus the size of the resource taxation is determined exogenously. However, we should analyse the optimal resource extraction rate that maximizes social welfare and then consider the size of resource taxation ψ that would realize such an optimal path. The evolution of consumption inequality under such an optimal policy should also be analysed. These extensions are promising directions for future research.

Third, to clarify the role of redistributive policy, we assume that resource tax revenues are used only for direct transfers from government to households. However, since this paper employs a stylized variety expansion growth model, there is an externality arising from the fact that innovators in the research sector cannot extract all of the surplus from the users of innovation. Therefore, analysing how the use of resource tax revenues to subsidize R&D affects economic growth and consumption inequality is a promising direction for future research.

Fourth, this study considers the case in which the resource tax rate changes over time. The analytical difficulties due to this formulation prevent us from analysing wealth inequality and income inequality in a way that is comparable to those in existing studies (e.g., Chu, 2010; Chu and Cozzi, 2018; Chu and Peretto, 2019; Chu et al, 2021). Although consumption inequality is the most relevant measure of inequality from an economic welfare perspective, there are few reliable empirical estimates of consumption inequality. Moreover, income (wealth) inequality is itself an interesting subject for analysis. Given these considerations, a more detailed analysis of the relationship between resource taxation policies and income (wealth) inequality is a promising direction for future research.

7 Conclusion

This paper extends the literature on exhaustible resource taxation by considering heterogeneous households with different assets and examines the effect of resource taxation on consumption inequality. As in the existing literature on endogenous growth models with exhaustible resources, resource taxes affect economic growth and the resource extraction rate only if the tax rate varies over time. We show that a lower resource tax growth rate slows resource extraction and promotes economic growth but increases consumption inequality. These results suggest that if the object of a government is to enhance economic growth without exacerbating consumption inequality, then the government should allocate more resource tax revenues for redistributive purposes. This paper also calibrates the model for quantitative analysis and finds that a lower growth rate of the tax on resource use causes a non-negligible increase in consumption inequality.

Appendix

Appendix A: Derivations of (22) and (23)

Derivations of (22)

Substituting (12) into (18) yields (22).

Derivations of (23)

From (11), (13) and $V_t = Y_t/(v_t N_t)$, we obtain

$$\frac{\dot{v}_t}{v_t} = r_t - \frac{V_t}{\epsilon}. \tag{A.1}$$

Using (A.1), $\gamma_{Y,t} = \gamma_{C,t} = (1/\sigma)(r_t - \rho)$ and $V_t = Y_t/(v_t N_t)$, we obtain

$$\frac{\dot{V}_t}{V_t} = -\frac{\sigma - 1}{\sigma} r_t + \frac{V_t}{\epsilon} - \frac{\rho}{\sigma} - \gamma_{N,t}. \tag{A.2}$$

Next, we derive r_t. Using (6), (8) and (10), we can rewrite (5) as

$$1 = \frac{\epsilon}{\epsilon - 1} N_t^{\frac{1}{1-\epsilon}} w_t^{1-\alpha} \left(\tau_t p_{H,t}\right)^{\alpha}. \tag{A.3}$$

From (3) and (A.3), we obtain

$$\frac{\dot{w}_t}{w_t} = -\frac{\alpha}{1-\alpha}(r_t + \gamma_\tau) + \frac{\gamma_{N,t}}{(\epsilon - 1)(1-\alpha)}. \tag{A.4}$$

Differentiating (12) with respect to time and using (A.4), we obtain

$$\frac{\dot{v}_t}{v_t} = -\frac{\alpha}{1-\alpha}(r_t + \gamma_\tau) - \left[1 - \frac{1}{(\epsilon - 1)(1-\alpha)}\right] \gamma_{N,t}. \tag{A.5}$$

Combining (A.1) and (A.5) yields

$$r_t = \frac{1-\alpha}{\epsilon} V_t - \alpha\gamma_\tau - \left[(1-\alpha) - \frac{1}{(\epsilon - 1)}\right] \gamma_{N,t}. \tag{A.6}$$

Substituting (A.6) into (A.2) yields (23).

Appendix B: Proof of Proposition 1

Solving (22) and (24) yields (25). Since $\gamma_{Y,t} = (1/\sigma)(r_t - \rho)$, we obtain (29). In the steady state, the labour allocated in the intermediate goods sector $N_t l_t$ is constant because $\dot{V}_t = 0$.[11] From (5) and (7), we obtain $Y_t = N_t^{\frac{1}{\epsilon-1}} (N_t l_t)^{1-\alpha} H_t^{\alpha}$, which implies

$$\gamma_{Y,t} = \frac{1}{\epsilon - 1}\gamma_{N,t} + \alpha\gamma_{H,t}. \tag{A.7}$$

Thus, we obtain (28). Differentiating (19) with respect to time and using (3), we obtain

$$r_t = \gamma_{Y,t} - \gamma_{H,t} - \gamma_\tau. \tag{A.8}$$

Substituting (A.8) into $\gamma_{Y,t} = (\frac{1}{\sigma})(r_t - \rho)$ yields

$$\gamma_{Y,t} = -\frac{\gamma_{H,t} + \gamma_\tau + \rho}{\sigma - 1}. \tag{A.9}$$

Combining (A.7) and (A.9) yields (26). From (26), we can see that the relation $H_t = H_0 e^{-\gamma_H^* t}$ holds. Using $H_t = H_0 e^{-\gamma_H^* t}$ and $\int_t^\infty H_t dt = S_t$, we obtain (27).

[11] From (12) and (18), the labour allocated in the intermediate goods sector $N_t l_t$ is given by $\frac{(1-\alpha)(\epsilon-1)}{\varphi\epsilon} V_t$.

Appendix C: Derivations of $V^* \equiv \epsilon(r^* - \gamma_Y^* + \gamma_N^*)$ and $C_t/W_t = r^* - \gamma_Y^*$

Derivation of $V^* \equiv \epsilon(r^* - \gamma_Y^* + \gamma_N^*)$

From (A.1) and $V_t = Y_t/(v_t N_t)$, we obtain

$$\frac{\dot{V}_t}{V_t} = \gamma_{Y_t} - \left(r_t - \frac{V_t}{\epsilon}\right) - \gamma_{N_t}. \tag{A.10}$$

Since $\dot{V}_t = 0$ in equilibrium, we have

$$V^* = \epsilon\left(r^* - \gamma_Y^* + \gamma_N^*\right). \tag{A.11}$$

Derivation of $C_t/W_t = r^* - \gamma_Y^*$

Since $C_t = Y_t$, (39) is rewritten as

$$\dot{\theta}_{W,t}(h) = \frac{Y_t}{W_t}\left[\theta_{W,t}(h) - \theta_{C,0}(h)\right]. \tag{A.12}$$

Using (21) and (35), the definition of W_t is rewritten as

$$\begin{aligned} W_t &= \int_t^\infty \left(w_s L + T_s\right) e^{-\int_t^s r_u du} ds + A_t. \\ &= \int_t^\infty w_s L e^{-\int_t^s r_u du} ds + \int_t^\infty T_s e^{-\int_t^s r_u du} ds + v_t^S + v_t N_t. \end{aligned} \tag{A.13}$$

By substituting (19) into (2) and rearranging it using (3), $\tau_s = \tau_t e^{\gamma_\tau (s-t)}$ and $Y_s = Y_t e^{\gamma_Y^* (s-t)}$, we have

$$v_t^S = \frac{1}{r^* - \gamma_Y^* + \gamma_\tau} \frac{\alpha(\epsilon - 1)}{\epsilon} \frac{Y_t}{\tau_t}. \tag{A.14}$$

Using (12) and $V_t = Y_t/(v_t N_t)$, we obtain $w_t = (\varphi/V^*)Y_t$. Substituting $w_t = (\varphi/V^*)Y_t$ into $\int_t^\infty w_s L e^{-\int_t^s r_u du} ds$ yields

$$\int_t^\infty w_s L e^{-\int_t^s r_u du} ds = \frac{\varphi L}{V^*} \frac{Y_t}{r^* - \gamma_Y^*}.$$

Using (22), the above equation is rewritten as

$$\int_t^\infty w_s L e^{-\int_t^s r_u du} ds = \left[\frac{(1-\alpha)(\epsilon - 1)}{\epsilon} + \frac{\gamma_N^*}{V^*}\right] \frac{Y_t}{r^* - \gamma_Y^*}. \tag{A.15}$$

In addition, substituting (17) and (19) into $\int_t^\infty T_s e^{-\int_t^s r_u du} ds$ yields

$$\int_t^\infty T_s e^{-\int_t^s r_u du} ds = \frac{1}{r^* - \gamma_Y^* + \gamma_\tau} \frac{\alpha(\epsilon - 1)}{\epsilon} \frac{Y_t}{\tau_t} \left(\frac{r^* - \gamma_Y^* + \gamma_\tau}{r^* - \gamma_Y^*} \tau_t - 1\right). \tag{A.16}$$

Thus, using (A.14), (A.15), (A.16) and $v_t N_t = \frac{Y_t}{V^*}$, W_t in (A.13) is rewritten as

$$W_t = \frac{Y_t}{\epsilon\left(r^* - \gamma_Y^*\right)} \left[\epsilon - 1 + \frac{\epsilon\left(r^* - \gamma_Y^* + \gamma_N^*\right)}{V^*}\right]. \tag{A.17}$$

Substituting (A.11) and $C_t = Y_t$ into (A.17) yields

$$\frac{C_t}{W_t} = r^* - \gamma_Y^*. \tag{A.18}$$

To ensure that lifetime utility is bounded, the relation $r^* - \gamma_Y^* = (\sigma - 1)\gamma_Y^* + \rho > 0$ must hold.

Appendix D: Derivations of (41), (44) and (49)

Derivation of (41)

By substituting (4) and (A.14) into (A.16), we obtain (41).

Derivation of (44)

Substituting (A.14), (A.15), (A.16), and $v_0 = Y_0/(V^* N_0)$ into (43) yields

$$\begin{aligned}\frac{W_0(h)\epsilon\left(r^*-\gamma_Y^*\right)}{Y_0} =&(1-\alpha)(\epsilon-1)+\frac{\epsilon\gamma_N^*}{V^*}+\lambda\alpha(\epsilon-1)\left[1-\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right]\\ &+\frac{\epsilon\left(r^*-\gamma_Y^*\right)}{V^*}\theta_N(h)\\ &+\alpha(\epsilon-1)\left\{1-\lambda\left[1-\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right]\right\}\theta_S(h).\end{aligned} \tag{A.19}$$

Using (A.11), (A.18), (A.19), and $C_t = Y_t$, we obtain

$$\begin{aligned}\theta_{W,0}(h) =&\frac{1}{\epsilon}\left\{(1-\alpha)(\epsilon-1)+\frac{\gamma_N^*}{r^*-\gamma_Y^*+\gamma_N^*}+\lambda\alpha(\epsilon-1)\left[1-\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right]\right\}\\ &+\frac{1}{\epsilon}\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}\theta_N(h)+\frac{\alpha(\epsilon-1)}{\epsilon}\left[1-\lambda+\lambda\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right]\theta_S(h).\end{aligned} \tag{A.20}$$

By substituting (42) into (A.20), we obtain (44).

Derivation of (49)

From (32) and (34), we obtain

$$\frac{\partial(r^*-\gamma_Y^*)}{\partial\gamma_\tau} = -\frac{(\sigma-1)\alpha\left[1+(1-\alpha)(\epsilon-1)\right]}{\sigma+(1-\alpha)(\epsilon-1)(1-\alpha+\alpha\sigma)}\begin{cases}\leq 0, & \text{for } \sigma\geq 1,\\ >0, & \text{for } \sigma<1.\end{cases} \tag{A.21}$$

Differentiating q_N with respect to γ_τ yields

$$\frac{\partial q_N}{\partial\gamma_\tau} = \frac{\frac{\partial(r^*-\gamma_Y^*)}{\partial\gamma_\tau}\gamma_N^*-\left(r^*-\gamma_Y^*\right)\frac{\partial\gamma_N^*}{\partial\gamma_\tau}}{\epsilon(r^*-\gamma_Y^*+\gamma_N^*)^2}.$$

By substituting (33) and (A.21) into the above equation, we obtain (49).

Appendix E: Quantitative analysis

Derivation of the ratio of resource tax revenues to GDP

In the R&D growth model, GDP is defined by $GDP_t = Y_t + v_t\dot{N}_t$. Thus, using $v_t = Y_t/(V^* N_t)$, we obtain

$$GDP_t = Y_t\left(1+\frac{\gamma_N^*}{V^*}\right). \tag{A.22}$$

From (17) and (19), we have

$$T_t = \frac{\alpha(\epsilon-1)}{\epsilon}\left(1-\frac{1}{\tau_t}\right)Y_t. \tag{A.23}$$

Substituting $\tau_t = \tau_0 e^{\gamma_\tau t}$ and (42) into (A.23) yields

$$T_t = \frac{\alpha(\epsilon-1)}{\epsilon}\left[1-\frac{1}{(1+\psi)\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_\tau}e^{\gamma_\tau t}}\right]Y_t. \tag{A.24}$$

Using (A.11), (A.22) and (A.24), the ratio of the resource tax revenues to GDP is given by

$$\frac{T_t}{GDP_t} = \frac{\epsilon\left(r^*-\gamma_Y^*+\gamma_N^*\right)}{\epsilon\left(r^*-\gamma_Y^*+\gamma_N^*\right)+\gamma_N^*}\frac{\alpha(\epsilon-1)}{\epsilon}\left[1-\frac{1}{(1+\psi)\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_\tau}e^{\gamma_\tau t}}\right]. \tag{A.25}$$

Since $\gamma_\tau = 0$ under the benchmark parameter values, we have

$$\frac{T_t}{GDP_t} = \frac{\epsilon\left(r^*-\gamma_Y^*+\gamma_N^*\right)}{\epsilon\left(r^*-\gamma_Y^*+\gamma_N^*\right)+\gamma_N^*}\frac{\alpha(\epsilon-1)}{\epsilon}\frac{\psi}{1+\psi}.$$

Derivation of the Gini coefficient of household assets

We define the household asset $E_0(h)$ at time 0 as the sum of the private asset $A_0(h)$ and the present value of the lump-sum tax/transfer $T_0(h)$ as follows:

$$E_0(h) \equiv A_0(h) + \int_0^\infty T_s(h)e^{-\int_t^s r_u du}ds. \tag{A.26}$$

By substituting (40) and (41) into (A.26), the household asset $E_0(h)$ is rewritten as

$$E_0(h) = \lambda TR_0 + \left[v_0^S + (1-\lambda)TR_0\right]\theta_S(h) + v_0 N_0 \theta_N(h). \tag{A.27}$$

Substituting (A.14), (A.16), and $v_0 = Y_0/(V^* N_0)$ into (A.27) yields

$$\begin{aligned}\frac{E_0(h)\epsilon\left(r^*-\gamma_Y^*\right)}{Y_0} =& \lambda\alpha(\epsilon-1)\left[1-\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right] \\ &+ \frac{\epsilon\left(r^*-\gamma_Y^*\right)}{V^*}\theta_N(h) \\ &+ \alpha(\epsilon-1)\left\{1-\lambda\left[1-\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right]\right\}\theta_S(h).\end{aligned} \tag{A.28}$$

Aggregating (A.28) across all households yields

$$\frac{E_0\epsilon\left(r^*-\gamma_Y^*\right)}{Y_0} = \alpha(\epsilon-1) + \frac{\epsilon\left(r^*-\gamma_Y^*\right)}{V^*}, \tag{A.29}$$

where $E_0 \equiv \int_0^1 E_0(h)dh$. Using (A.11), (A.28), and (A.29), the household asset share $\theta_E(h) \equiv E_0(h)/E_0$ is given by

$$\begin{aligned}\theta_E(h) =& \frac{\alpha(\epsilon-1)}{\alpha(\epsilon-1)+\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}}\left[1-\lambda+\lambda\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right]\\ &+\frac{\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}}{\alpha(\epsilon-1)+\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}}\theta_N(h)\\ &+\frac{\alpha(\epsilon-1)}{\alpha(\epsilon-1)+\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}}\lambda\left[1-\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right].\end{aligned} \tag{A.30}$$

By substituting (42) into (A.30), we obtain

$$\theta_E(h) = (1-\beta_S-\beta_N)+\beta_S\theta_S(h)+\beta_N\theta_N(h), \tag{A.31}$$

where $\beta_S \equiv \frac{\alpha(\epsilon-1)}{\alpha(\epsilon-1)+\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}}(1-\frac{\psi}{1+\psi}\lambda)$ and $\beta_N \equiv \frac{\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}}{\alpha(\epsilon-1)+\frac{r^*-\gamma_Y^*}{r^*-\gamma_Y^*+\gamma_N^*}}$. The Lorenz curve of the household asset $\mathcal{L}_E(h)$ is defined by $\mathcal{L}_E(h) \equiv \int_0^h \theta_E(z)dz$. Thus, the Gini coefficient of the household asset σ_E^G is given by $\sigma_E^G \equiv 1-2\int_0^1 \mathcal{L}_E(h)dh$. By substituting (A.31) into the definition of σ_E^G, we obtain

$$\sigma_E^G = \beta_S\sigma_S^G + \beta_N\sigma_N^G. \tag{A.32}$$

Tables 2 and 3 show three different pairs of σ_S^G and σ_N^G that ensure that the relation $\sigma_E^G = 0.83$ holds in the benchmark case.

Appendix F: Discussion

If we ignore the fiscal rule defined in (42) and assume that the initial tax level τ_0 is constant, from (A.20), the standard deviation of the consumption share is expressed as

$$\sigma_C = \sqrt{\hat{q}_S^2\sigma_S^2 + q_N^2\sigma_N^2 + 2\hat{q}_S q_N \sigma_{SN}}, \tag{A.33}$$

where $\hat{q}_S \equiv \frac{\alpha(\epsilon-1)}{\epsilon}\left[1-\lambda+\lambda\frac{r^*-\gamma_Y^*}{\tau_0(r^*-\gamma_Y^*+\gamma_\tau)}\right]$. Thus, by differentiating σ_C with respect to γ_τ and using (25), (28), and (29), we obtain

$$\frac{\partial\sigma_C}{\partial\gamma_\tau} = \frac{1}{2\sigma_C}\left(\underbrace{\frac{\partial\sigma_C^2}{\partial q_N}}_{(>0)}\frac{\partial q_N}{\partial\gamma_\tau} + \underbrace{\frac{\partial\sigma_C^2}{\partial\hat{q}_S}}_{(>0)}\frac{\partial\hat{q}_S}{\partial\gamma_\tau}\right) < 0, \text{ for } \sigma \geq 1. \tag{A.34}$$

Equation (A.34) shows that the sign of $\partial\sigma_C/\partial\gamma_\tau$ depends upon the signs of $\partial q_N/\partial\gamma_\tau$ and $\partial\hat{q}_S/\partial\gamma_\tau$. From (49), when $\sigma \geq 1$, we have $\partial q_N/\partial\gamma_\tau \leq 0$. Moreover, by differentiating $\hat{q}_S$ with respect to γ_τ, we obtain

$$\frac{\partial\hat{q}_S}{\partial\gamma_\tau} = \frac{\alpha(\epsilon-1)\lambda}{\epsilon\tau_0}\frac{r^*-\gamma_Y^*}{(r^*-\gamma_Y^*+\gamma_\tau)^2}\left[\frac{\partial(r^*-\gamma_Y^*)}{\partial\gamma_\tau}\frac{\gamma_\tau}{r^*-\gamma_Y^*}-1\right] < 0, \text{ for } \sigma \geq 1, \tag{A.35}$$

where we have used $\partial(r^*-\gamma_Y^*)/\partial\gamma_\tau \leq 0$ for $\sigma \geq 1$ from (A.21). Thus, as shown in (A.34), when $\sigma \geq 1$, a higher resource tax growth rate reduces consumption inequality not only by lowering the value of the weight parameter q_N for $\theta_N(h)$ but also by lowering the value of the weight parameter $\hat{q}_S$ for $\theta_S(h)$.

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