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Should Governments Subsidize Resource-Using Variety-Expanding Innovation or Resource-Substituting Innovation?

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Should Governments Subsidize Resource-Using Variety-Expanding Innovation or Resource-Substituting Innovation? *

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Abstract

This study introduces endogenous resource-substituting innovation into a variety-expanding endogenous growth model with polluting non-renewable resources. The resulting task-based framework highlights the trade-off between resource-using variety-expanding innovation and resource-substituting innovation. We examine how subsidies for these two types of innovation affect economic growth and welfare, and how environmental policies that slow resource extraction and mitigate pollution shape these effects. Subsidies for new-variety R&D promote growth through faster variety expansion but reduce it through greater reliance on resource extraction, reflected in a lower share of firms adopting resource-substituting production methods and higher resource intensity in aggregate production. Subsidies for resource-substituting innovation have the opposite effects. Calibrating the model, we find that raising subsidies for new-variety R&D is more likely to improve welfare in resource-rich economies, whereas raising subsidies for resource-substituting innovation is more likely to improve welfare in resource-poor economies. We also find that more stringent environmental policies that conserve resources and mitigate pollution strengthen the welfare gains from subsidies for resource-substituting innovation, while weakening those from new-variety R&D subsidies.

Keywords: Non-Renewable Resources · Resource-Substituting Innovation · R&D-based Growth

JEL Classification Numbers: O31 · O44 · Q55

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1 Introduction

Reducing fossil-fuel use and curbing greenhouse-gas emissions are widely recognized as major challenges in addressing climate change and ensuring the long-run sustainability of living standards (e.g., IPCC, 2014). While a large literature emphasizes market-based policies such as carbon taxes, emissions-trading schemes, fossil-fuel taxes, and subsidy reforms that discourage the extraction and consumption of polluting non-renewable resources, many governments increasingly support the development of resource-substituting technologies (e.g., Nordhaus, 2021). By improving resource efficiency, replacing resource inputs with alternative inputs, or providing new production methods, such technologies reduce dependence on scarce natural resources. Unlike environmental taxes, support for resource-substituting innovation can often be justified simultaneously on environmental, industrial, and innovation-policy grounds (e.g., Hasna et al., 2023). As a result, understanding the role of resource-substituting innovation in achieving both environmental sustainability and long-run economic growth has become increasingly important.

However, different forms of innovation may have very different implications for resource dependence. Many growth-enhancing technologies initially emerge as production methods that rely on material resources, while subsequent innovation often reduces resource requirements through efficiency improvements or input substitution. For example, the diffusion of automobiles, petrochemical products, semiconductor technologies, and digital infrastructure was accompanied by substantial increases in the use of energy, minerals, and other material inputs. Over time, further innovation reduced the resource intensity of these technologies through efficiency improvements and the development of substitute inputs. Consequently, governments face a fundamental policy trade-off between supporting the creation of new varieties that drive long-run growth and promoting resource-substituting innovation that reduces resource dependence.

This paper develops a variety-expanding endogenous growth model with polluting non-renewable resources in which skilled labor can be allocated either to new-variety innovation or to resource-substituting technology development. Each new intermediate-good variety is initially developed as a resource-using production technology, while subsequent resource-substituting innovation enables the same variety to be produced without material resources. Building on the task-based framework of Zeira (1998) and Acemoglu and Restrepo (2018b), we interpret resource-substituting innovation broadly as the development of resource-dependence-reducing technologies, ranging from resource-saving innovations that improve resource efficiency or replace resource-intensive inputs with alternative inputs to backstop technologies that ultimately eliminate dependence on exhaustible resources.[1] Within this framework, we examine how subsidies for these two forms of innovation affect economic growth, resource dependence, pollution, and welfare, and how environmental policies that slow resource extraction shape these effects.

The resulting task-based framework highlights a fundamental trade-off between resource-using variety-expanding innovation and resource-substituting innovation. Subsidies for new-variety R&D promote growth through faster variety expansion but reduce growth through a greater reliance on resource extraction, reflected in a lower share of firms adopting resource-substituting production methods and a higher resource intensity of aggregate production. Subsidies for resource-substituting innovation have the opposite effects. Calibrating the model, we find that raising subsidies for new-variety R&D is more likely to improve welfare in resource-rich economies, whereas raising subsidies for resource-substituting innovation is more likely to improve welfare in resource-poor economies. The intuition is that each policy tends to shift the production structure toward a level of resource intensity that is better aligned with the economy's resource endowment, thereby improving consumption and welfare.

We further show that more stringent environmental policies, which conserve resources and mitigate pollution, strengthen the welfare gains from subsidies for resource-substituting innovation while weakening those from subsidies for new-variety R&D. The reason is that stringent environmental policies already generate higher economic growth by alleviating resource scarcity. As a result, they reduce both the additional growth benefits associated with higher subsidies for new-variety R&D and the additional growth costs associated with higher subsidies for resource-substituting innovation.

Finally, we find that accounting explicitly for transitional dynamics improves the welfare effects of an increase in the subsidy rate for new-variety R&D, while reducing those of an increase in the subsidy rate for resource-substituting innovation. A higher subsidy rate for new-variety R&D raises expected future resource demand by increasing the future resource intensity of production. This encourages resource owners

[1] Resource-saving technologies reduce resource use through efficiency improvements and task-level substitutions, whereas backstop technologies provide system-level substitutes that can ultimately eliminate dependence on a particular resource.

to postpone extraction, thereby reducing the present discounted value of pollution damages. By contrast, a higher subsidy rate for resource-substituting innovation lowers expected future resource demand, induces earlier resource extraction, and increases the present discounted value of pollution damages.

This paper relates to three main strands of the literature. First, it contributes to the literature on endogenous growth models with exhaustible resources and backstop technologies (e.g., Di Vita, 2001, 2004; Valente, 2011; van der Meijden and Smulders, 2017, 2018).[2] Among these studies, our paper is most closely related to van der Meijden and Smulders (2017, 2018), who employ R&D-based growth models to examine how resource-substituting technologies, such as backstop technologies, affect the direction of R&D and long-run economic growth. van der Meijden and Smulders (2017) show how the cost of backstop technologies and agents' expectations affect innovators' R&D choices and fossil-fuel suppliers' extraction decisions, thereby determining whether fossil fuels are eventually phased out. van der Meijden and Smulders (2018) use a variety-expanding growth model to analyze the dynamics of innovation and growth during the transition from fossil fuels to backstop technologies. In contrast, we do not take the availability of resource-substituting technologies as given. Building on the task-based framework of Zeira (1998) and Acemoglu and Restrepo (2018b), we explicitly model their endogenous creation through R&D investment.[3] We then examine how the allocation of innovative effort between new-variety innovation and resource-substituting innovation, together with environmental policy and innovation subsidies, shapes economic growth, resource dependence, and welfare.

Second, this paper relates to the literature on dynamic models of recycling and the Green Paradox that consider renewable backstops as substitutes for non-renewable resources (e.g., Lafforgue and Rougé, 2019; van der Ploeg and Withagen, 2012, 2015).[4] Lafforgue and Rougé (2019) show how R&D-driven improvements in recycling technology can transform recycled waste into a substitute for non-renewable resources and eventually lead to a fully recycling economy. van der Ploeg and Withagen (2012) show

[2] Di Vita (2001, 2004) considers waste-recycling technologies as substitutes for non-renewable resources. Valente (2011) explores the optimal timing of the transition from fossil fuels to backstop technologies in a variety-expanding growth model.

[3] Outside the R&D-based growth literature, Dasgupta and Heal (1974) and Dasgupta and Stiglitz (1981) allow for the stochastic arrival of a backstop technology. Kamien and Schwartz (1978) endogenize the invention process through R&D, while Tsur and Zemel (2003, 2011) analyze R&D-driven transitions from fossil fuels to backstop technologies. See the Introduction of van der Meijden and Smulders (2017) for a survey.

[4] See, for example, van der Ploeg and Withagen (2015) for a survey of the Green Paradox literature.

that, in the absence of a carbon tax, the anticipation of a cheaper renewable backstop increases current CO_2 emissions. Like these studies, we are interested in resource-substituting innovation and in how expectations about future resource-substituting technologies affect fossil-fuel suppliers' incentives. Unlike them, however, we study these issues within an R&D-based endogenous growth framework, focusing on the trade-off between resource-using variety-expanding innovation and resource-substituting innovation and its implications for long-run growth.

Third, this paper relates to the literature on automation and economic growth that employs the task-based framework (e.g., Zeira, 1998; Acemoglu and Restrepo, 2018a, 2018b; Hemous and Olsen, 2022; Chu et al., 2023). Acemoglu and Restrepo (2018a) emphasize that the task-based approach has an important advantage over traditional capital-augmenting and labor-augmenting frameworks in capturing the substitution of machines for labor across an expanding range of tasks. Analogously, our framework captures the gradual substitution of material-resource inputs by resource-substituting technologies across an expanding range of production tasks, not only in the energy sector but also throughout the upstream and downstream stages of the production process. In this sense, our paper is complementary to studies that examine backstop technologies in the energy sector (e.g., van der Meijden and Smulders, 2017, 2018) and through waste recycling and resource recovery (e.g., Di Vita, 2001, 2004; Lafforgue and Rougé, 2019). Furthermore, our modeling of resource-substituting innovation is closely related to the treatment of automation technology development in Hemous and Olsen (2022) and Chu et al. (2023). Unlike these studies, however, we focus on the trade-off between resource-using variety-expanding innovation and resource-substituting innovation and on its implications for economic growth, resource dependence, and welfare.

The remainder of the paper is organized as follows. Section 2 presents the basic model. Section 3 characterizes the steady-state equilibrium and examines the growth and welfare effects of two R&D subsidy policies. Section 4 presents numerical simulations and compares the steady-state and transitional effects of these policies, with particular attention to the role of environmental policy. Section 5 concludes.

2 Model

Building on the task-based framework of Zeira (1998) and Acemoglu and Restrepo (2018b), we introduce endogenous resource-substituting innovation into a variety-expanding endogenous growth model with polluting non-renewable resources. We consider a sequence of resource-using variety innovation and subsequent resource-substituting innovation. Each new intermediate-good variety is initially developed through R&D as a production technology that relies on material resources. Subsequent investment in resource-substituting innovation enables the same intermediate good to be produced without material resources.

More generally, we interpret resource-substituting innovation as the development of resource-dependence-reducing technologies. This broad concept encompasses both resource-saving technologies and backstop technologies. While resource-saving technologies reduce resource requirements through efficiency improvements and task-level substitution, backstop technologies reduce or eliminate dependence on scarce resources through system-wide substitution. The distinction is therefore one of degree and scope rather than category, reflecting different levels of resource substitution. In this sense, backstop technology development can be viewed as the limiting case of resource-substituting innovation in our task-based framework.

2.1 Resource-Extracting Firm

Natural resources are non-renewable. The resource stock S_t is depleted through the extraction of resources M_t for production, so that the law of motion for the resource stock is given by

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

We assume that resource extraction is costless. A competitive price-taking resource-extracting firm maximizes the present value of intertemporal profits,

$$\int_0^\infty p_{m,t} M_t e^{-\int_0^t r_u du} dt,$$

where $p_{m,t}$ denotes the resource price and r_t denotes the interest rate, subject to (1). This yields the familiar Hotelling rule:

$$\frac{\dot{p}_{m,t}}{p_{m,t}} = r_t. \tag{2}$$

As usual, the transversality condition implies that $\lim_{t\to\infty} S_t = 0$ and $\int_0^\infty M_t dt = S_0$.

The use of resources in production, M_t, generates a proportional flow of pollution. The pollution stock evolves according to the following law of motion:

$$\dot{Z}_t = \eta M_t - \delta Z_t, \tag{3}$$

where $\eta > 0$ denotes the pollution flow per unit of resource use, and $\delta \in (0,1)$ denotes the depreciation rate of the pollution stock. This formulation is standard in models describing the dynamics of carbon accumulation (e.g., Grimaud and Rouge, 2014), where the carbon stock increases with the flow ηM_t, such as CO_2 emissions, and decreases through natural removals, δZ_t. Given $Z_0 = 0$,[5] the pollution stock at time t is given by

$$Z_t = \eta \int_0^t M_\tau e^{-\delta(t-\tau)} d\tau.$$

2.2 Final Good

Competitive firms produce a final good using the following Cobb–Douglas aggregator over a continuum of n_t differentiated intermediate goods:[6]

$$y_t = A_t \exp\left(\frac{1}{n_t}\int_0^{n_t} \ln x_t(i)\, di\right), \quad A_t = A n_t^\kappa, \tag{4}$$

[5]To maintain the tractability of the model, we normalize the initial value Z_0 to zero and assume that the depreciation rate of the pollution stock, δ, is constant.

[6]Following Grossman and Helpman (1991), we adopt a Cobb–Douglas aggregator, which ensures that all operating firms earn the same monopoly profit. In contrast, under a CES aggregator, profits would differ depending on whether a firm has adopted resource-substituting technology. Although this distinction does not affect our main results, it complicates the analysis of the trade-off between investment in new-variety innovation and resource-substituting technology development, thereby necessitating a substantially more complex analytical framework.

where $x_t(i)$ denotes the quantity of intermediate good $i \in [0, n_t]$. Following Romer (1990), we introduce the productivity parameters $A > 0$ and $\kappa > 1$, and assume that total factor productivity, A_t, depends positively on the stock of existing blueprints, n_t. The parameter κ captures the positive productivity externalities arising from both the cumulative outcomes of past research and the learning-by-doing effects generated by the expansion of input varieties. Owing to these intertemporal and intratemporal knowledge spillovers, output in the final-good sector increases with the number of intermediate inputs. The conditional demand function for intermediate good $x_t(i)$ is given by

$$x_t(i) = \frac{y_t}{n_t p_t(i)}, \tag{5}$$

where $p_t(i)$ denotes the price of intermediate good $x_t(i)$.

2.3 Intermediate Goods

There is a continuum of intermediate goods of measure n_t, indexed by $i \in [0, n_t]$. Each intermediate good is produced by a monopolist that holds the exclusive right to its production. In this economy, each new variety of intermediate goods is initially developed through R&D as a production technology that requires material resources. Subsequent investment in resource-substituting innovation enables the same intermediate good to be produced without material resources, using low-skilled labor instead.

Accordingly, at time t, there are two types of intermediate-good firms ($j \in \{M, R\}$): $n_{M,t}$ firms that use material resources as inputs ($j = M$), and $n_{R,t}$ firms that have adopted resource-substituting technology and produce using low-skilled labor instead of material resources ($j = R$). These satisfy $n_{M,t} + n_{R,t} = n_t$. We refer to the former as resource-using firms and the latter as resource-substituting firms. Let $\theta_t \in (0, 1)$ denote the share of resource-substituting firms, $\theta_t \equiv \frac{n_{R,t}}{n_t}$, so that the share of resource-using firms is $1 - \theta_t$.

2.3.1 Material-Resource-Using Firms

If a firm has not yet adopted backstop technology, production requires material-resource inputs, and the production function is given by

$$x_t(i) = \frac{1}{a_M} m_t(i), \tag{6}$$

where $a_M > 0$ is a productivity parameter and $m_t(i)$ denotes the amount of raw materials used by firm i. The profit of intermediate-good firm i that uses material resources as production inputs is given by

$$\pi_{M,t}(i) = [p_t(i) - a_M(1+\iota_t)p_{m,t}]\, x_t(i),$$

where $p_{m,t}$ denotes the price of material resources and ι_t is a unit ad valorem tax (or subsidy) on resource use, introduced to address the distortion arising from firms' failure to internalize the negative externalities associated with the use of polluting non-renewable resources. Although the tax is levied on resource use, M_t, rather than on the pollution flow, ηM_t, the qualitative implications are unchanged because the two are linearly related. For notational convenience, we define $\tau_t \equiv 1 + \iota_t$.[7] If $\tau_t \leq 1$ (i.e., $\iota_t \leq 0$), the government subsidizes resource use, whereas if $\tau_t > 1$ (i.e., $\iota_t > 0$), the government taxes resource use.

Moreover, following Daubanes and Grimaud (2010), we restrict our analysis to the case in which the resource tax evolves at a constant growth rate and does not decline too rapidly over time. Specifically, we assume that[8]

$$g_{\tau,t} \equiv \frac{\dot{\tau}_t}{\tau_t} = g_\tau > -\rho, \qquad \forall t \in [0, \infty).$$

Therefore, the environmental tax is given by $\tau_t = \tau_0 e^{g_\tau t}$. In the literature on non-renewable resources, it is well recognized that controlling pollution generated by resource extraction generally requires a time-varying resource tax policy (e.g., Grimaud and Rougé 2005, 2014; Daubanes and Grimaud 2010; Pittel

[7] In what follows, we use the multiplicative tax factor τ_t rather than the ad valorem tax rate ι_t.

[8] To satisfy the transversality condition $\int_0^\infty M_t dt = S_0$, the steady-state equilibrium must satisfy $g_{M,t} = -(\rho + g_\tau) < 0$.

and Bretschger 2010; Tabata 2026). To capture this feature in a tractable manner, theoretical models often adopt the above tax specification. It is also well known that, under this specification, a lower tax growth rate g_τ reduces the future resource price faced by intermediate-good firms, $\tau_t p_{m,t}$, relative to the path that would prevail in the absence of the policy change. As a result, future resource demand increases, whereas current resource demand decreases. This effect induces resource-producing firms to slow the pace of resource extraction, thereby mitigating the negative externality associated with pollution. Accordingly, since a lower tax growth rate g_τ corresponds to a stricter environmental policy that slows resource extraction and reduces pollution, we focus on its effects in the analysis below.

Given the Cobb–Douglas aggregator in (4), the unconstrained monopoly price would be infinite. We therefore follow Goh and Olivier (2002) and impose a price-regulation policy under which the markup ratio cannot exceed $\mu > 1$, so that $p_t(i) \leq \mu a_M \tau_t p_{m,t}$.[9] Profit maximization then implies $p_t(i) = \mu a_M \tau_t p_{m,t} \equiv p_{M,t}$, which yields

$$x_t(i) = \frac{y_t}{n_t p_{M,t}} \equiv x_{M,t}, \tag{7}$$

and

$$\pi_{M,t}(i) = \frac{\mu - 1}{\mu} \frac{y_t}{n_t} \equiv \pi_{M,t}. \tag{8}$$

Since only material-resource-using firms use raw materials, the market-clearing condition for raw materials at time t is

$$a_M x_{M,t} n_{M,t} = M_t. \tag{9}$$

[9] Goh and Olivier (2002) consider an environment in which each intermediate-goods sector contains many potential competitors capable of producing the same product, albeit less efficiently than the patent-holding monopolistic firm. They interpret $\mu > 1$ as a patent-breadth parameter that determines monopoly power by specifying the range of technologies covered by patent protection.

2.3.2 Resource-Substituting-Technology-Using Firms

If a firm has adopted resource-substituting technology, production uses low-skilled labor, and the production function is given by

$$x_t(i) = \frac{1}{a_R} l_t(i), \tag{10}$$

where $a_R > 0$ is a productivity parameter and $l_t(i)$ denotes the amount of low-skilled labor employed by firm i. The profit of intermediate-good firm i that has adopted resource-substituting technology is given by

$$\pi_{R,t}(i) = [p_t(i) - a_R w_{l,t}]\, x_t(i),$$

where $w_{l,t}$ denotes the wage rate of low-skilled labor. As before, we impose a price-regulation policy under which $p_t(i) \leq \mu a_R w_{l,t}$. Profit maximization then implies $p_t(i) = \mu a_R w_{l,t} \equiv p_{R,t}$, which yields

$$x_t(i) = \frac{y_t}{n_t p_{R,t}} \equiv x_{R,t}, \tag{11}$$

and

$$\pi_{R,t}(i) = \frac{\mu - 1}{\mu} \frac{y_t}{n_t} \equiv \pi_{R,t}. \tag{12}$$

Since only resource-substituting-technology-using firms employ low-skilled labor, the market-clearing condition for low-skilled labor at time t is

$$a_R x_{R,t} n_{R,t} = L, \tag{13}$$

where L is the fixed supply of low-skilled labor provided by households.

2.4 Resource-Substituting Technology Adoption

Firms that currently employ material-resource-using technology can adopt resource-substituting technology and switch from material resources to low-skilled labor as their production input by acquiring the corresponding patents, provided that entrepreneurs successfully develop resource-substituting technology for the corresponding intermediate good. More precisely, adoption occurs when the newly developed resource-substituting technology yields a lower marginal cost than the existing resource-based technology; that is,

$$a_R w_{l,t} \leq a_M \tau_t p_{m,t}. \tag{14}$$

Following Chu et al. (2023), we focus on the case in which the newly developed resource-substituting technology is sufficiently efficient that condition (14) always holds in equilibrium. As a result, entrepreneurs have sufficiently strong incentives to invest in resource-substituting technology development. In the steady-state equilibrium, as shown in Appendix A, the resource price $p_{m,t}$ grows at the interest rate r according to the Hotelling rule in equation (2), while the resource tax grows at the rate g_τ and the low-skilled wage $w_{l,t}$ grows at the output growth rate $g_y = r - \rho$. Therefore, condition (14) is satisfied for a wide range of parameter values, provided that the tax growth rate satisfies the restriction $g_\tau > -\rho$ discussed above. This result further implies that there exists a broad region of the parameter space in which condition (14) also holds along the transition path, particularly when the economy is sufficiently close to its steady-state equilibrium.

It is worth noting that the technology-adoption framework developed above can alternatively be interpreted as a task-based framework, following Acemoglu and Restrepo (2018b) and Hemous and Olsen (2022). Under this interpretation, final-good production requires n_t distinct tasks. For each task, the final-good producer chooses the cost-minimizing production technology, determining whether the task is performed using a material-resource-based technology or resource-substituting technology. Since the equilibrium allocation in our model likewise assigns each task to the cost-minimizing technology, all of the results derived below remain unchanged under this alternative task-based interpretation.

However, incorporating an explicit technology-choice problem for final-good producers and analyzing entrepreneurs' investment decisions in new intermediate-good varieties and resource-substituting technology within such a framework would require a modeling structure that departs from the standard textbook R&D-based growth model. Although feasible, doing so would substantially increase the complexity of the model for reasons that are largely unrelated to the paper's main mechanisms and results. We therefore adopt the present framework in the interest of analytical tractability and expositional clarity.

2.5 Innovation in New Varieties and Resource-Substituting Technology Development

2.5.1 No-Arbitrage Conditions

Equations (8) and (12) imply that $\pi_{M,t}(i) = \pi_{M,t}$ and $\pi_{R,t}(i) = \pi_{R,t}$ for all firms of a given type. Therefore, firm values are also identical within each group, i.e., $v_{M,t}(i) = v_{M,t}$ and $v_{R,t}(i) = v_{R,t}$.

The no-arbitrage condition that determines the value of a material-resource-using intermediate-good firm, $v_{M,t}$, is given by

$$r_t = \frac{\pi_{M,t} + \dot{v}_{M,t} - \alpha_t v_{M,t}}{v_{M,t}}, \tag{15}$$

which states that the rate of return on holding the firm is equal to the interest rate. The return consists of monopoly profit $\pi_{M,t}$, capital gain $\dot{v}_{M,t}$, and the expected capital loss $\alpha_t v_{M,t}$, where α_t denotes the arrival rate of resource-substituting innovation, as explained below.

Similarly, the no-arbitrage condition that determines the value of a resource-substituting firm, $v_{R,t}$, is

$$r_t = \frac{\pi_{R,t} + \dot{v}_{R,t}}{v_{R,t}}, \tag{16}$$

which states that the rate of return on holding the firm is also equal to the interest rate. The return consists of monopoly profit $\pi_{R,t}$ and capital gain $\dot{v}_{R,t}$.

2.5.2 Innovation in New Varieties

Competitive entrepreneurs employ high-skilled labor $h_{n,t}$ to develop blueprints for new varieties of intermediate goods whose production processes use material resources as inputs. The R&D process is subject to uncertainty. Over a short time interval dt, each entrepreneur succeeds in inventing a blueprint for a new intermediate-good variety with probability $\lambda_t dt$. As in Romer (1990), we assume that the number of potential entrepreneurs engaged in the invention of new intermediate-good varieties is equal to the current number of blueprints, n_t. This variable serves as a proxy for the stock of cumulative knowledge that has not yet become obsolete. Accordingly, the stock of product varieties (i.e., the stock of knowledge) evolves according to

$$\dot{n}_t = \lambda_t n_t, \quad \Leftrightarrow \quad g_{n,t} = \frac{\dot{n}_t}{n_t} = \lambda_t, \tag{17}$$

where $g_{n,t}$ denotes the growth rate of the number of intermediate-good varieties.

The Poisson arrival rate of innovation, λ_t, is given by

$$\lambda_t = \varphi_t h_{n,t}. \tag{18}$$

To capture two sources of R&D externalities commonly discussed in the literature, we assume that $\varphi_t = \varphi n_t^{\psi} \bar{h}_{n,t}^{\psi-1}$, where $\bar{h}_{n,t} \equiv \frac{H_{n,t}}{n_t}$ and $H_{n,t} \equiv h_{n,t} n_t$. Here, $\varphi > 0$ is an innovation-productivity parameter. The term n_t captures the positive externality arising from knowledge spillovers that increase each entrepreneur's probability of successful innovation. Since $H_{n,t}$ denotes aggregate high-skilled labor employed in new-variety R&D, $\bar{h}_{n,t}$ represents the average amount of high-skilled labor per R&D firm. A higher level of $\bar{h}_{n,t}$ indicates greater overlap in research activities across entrepreneurs, which gives rise to duplication in research effort and reduces the social return to R&D. Thus, the parameter $\psi \in (0, 1)$ captures an intratemporal duplication externality, as in Jones and Williams (2000), and determines the degree of decreasing returns to scale in R&D at the aggregate level. In equilibrium, since $\bar{h}_{n,t} = h_{n,t}$, the aggregate arrival rate of innovation is given by $\lambda_t = \varphi H_{n,t}^{\psi}$.

Given the value of a newly created intermediate-good firm, $v_{M,t}$, the expected profit of an entrepreneur is $\lambda_t v_{M,t} - (1-s)w_{h,t}h_{n,t}$. In a symmetric equilibrium, the free-entry condition for R&D aimed at creating new intermediate-good varieties is

$$\lambda_t v_{M,t} = (1-s)w_{h,t}h_{n,t}, \quad \Leftrightarrow \quad \varphi n_t v_{M,t} = (1-s)w_{h,t}H_{n,t}^{1-\psi}, \tag{19}$$

where $s \in [0,1)$ is the subsidy rate for R&D directed toward the creation of new intermediate-good varieties, and $w_{h,t}$ is the wage rate of high-skilled labor.

2.5.3 Resource-Substituting Technology Development

Competitive entrepreneurs also employ high-skilled labor $h_{R,t}$ to develop resource-substituting technology for firms that still rely on material resources as production inputs. As before, the outcome of this investment is subject to uncertainty. Over a short time interval dt, each entrepreneur succeeds in developing resource-substituting technology with probability $\alpha_t dt$. Naturally, the number of new resource-substituting technologies developed at time t is constrained by the number of firms that have not yet adopted resource-substituting technology. To capture this in a parsimonious way, following Aghion and Howitt (2009), we assume that the number of potential entrepreneurs engaged in resource-substituting technology development is equal to the number of firms that have not yet adopted it, $n_{M,t}$.[10]

This specification implies that the evolution of the number of resource-substituting firms is given by

$$\dot{n}_{R,t} = \alpha_t n_{M,t}, \quad \Leftrightarrow \quad g_{n_{R,t}} = \frac{\dot{n}_{R,t}}{n_{R,t}} = \alpha_t \frac{1-\theta_t}{\theta_t}, \tag{20}$$

where $g_{n_{R,t}}$ denotes the growth rate of the number of intermediate-good varieties produced using resource-substituting technology.

[10]More precisely, following the R&D specification of the Schumpeterian growth model of Aghion and Howitt (2009), we assume that each intermediate-good sector that has not yet adopted resource-substituting technology is matched with a single entrepreneur who undertakes R&D to develop resource-substituting technology for that intermediate good.

The Poisson arrival rate of resource-substituting innovation, α_t, is given by

$$\alpha_t = \phi_t h_{R,t}. \tag{21}$$

To capture the effects of knowledge spillovers and duplication in R&D activities, we assume that $\phi_t = \phi n_t^{\psi}(1-\theta_t)\bar{h}_{R,t}^{\psi-1}$, where $\bar{h}_{R,t} \equiv \frac{H_{R,t}}{n_t}$, $H_{R,t} \equiv h_{R,t} n_{M,t}$. Here, $\phi > 0$ is a productivity parameter for resource-substituting technology development. As before, n_t captures the positive externality arising from knowledge spillovers that increase each entrepreneur's probability of successful innovation. The term $\bar{h}_{R,t}$ captures duplication in research activities across entrepreneurs, which gives rise to duplication in research effort and reduces the social return to R&D. Accordingly, $\psi \in (0,1)$ determines the degree of decreasing returns to scale in resource-substituting innovation at the aggregate level. The endogenous variable $\theta_t \in (0,1)$ denotes the fraction of firms that use resource-substituting technology at time t. The term $(1-\theta_t)$ captures the idea that a larger mass of firms still relying on material resources implies greater scope for the adoption of resource-substituting technology, thereby increasing each entrepreneur's probability of successful innovation. In equilibrium, since $\bar{h}_{R,t} = h_{R,t}(1-\theta_t)$, the aggregate arrival rate of resource-substituting innovation is given by $\alpha_t = \phi H_{R,t}^{\psi}$.

Given the value $v_{R,t}$ created by a successful resource-substituting innovation, the expected profit of an entrepreneur is $\alpha_t v_{R,t} - (1-\sigma)w_{h,t}h_{R,t}$. In a symmetric equilibrium, the free-entry condition for resource-substituting technology development is

$$\alpha_t v_{R,t} = (1-\sigma)w_{h,t}h_{R,t} \quad \Leftrightarrow \quad \phi(1-\theta_t)n_t v_{R,t} = (1-\sigma)w_{h,t}H_{R,t}^{1-\psi}, \tag{22}$$

where $\sigma \in [0,1)$ is the subsidy rate for resource-substituting technology development.

Finally, since high-skilled labor is employed either in R&D aimed at creating new varieties or in resource-substituting technology development, the market-clearing condition for high-skilled labor at time t is

$$H_{n,t} + H_{R,t} = 1, \tag{23}$$

where the total supply of high-skilled labor provided by households is normalized to unity.

2.6 Households

The representative household has the following utility function:

$$U = \int_0^\infty e^{-\rho t} \left(\ln c_t - \omega Z_t\right) dt, \tag{24}$$

where $\rho > 0$ is the subjective discount rate, c_t denotes consumption, $\omega > 0$ is the pollution externality parameter, and Z_t is the stock of pollution. For ease of comparison, we adopt the pollution specification used by Grimaud and Rouge (2014).

The household holds equity in resource-extracting firms and intermediate-good firms, supplies L units of low-skilled labor and one unit of high-skilled labor, and chooses consumption and saving to maximize utility subject to the following asset accumulation equation:

$$\dot{a}_t = r_t a_t + p_{m,t} M_t + \left(1 - \tau_{L,t}\right) \left(w_{h,t} + w_{l,t} L\right) + T_t - c_t, \tag{25}$$

where a_t denotes the value of assets (i.e., shares in intermediate-good firms), r_t is the interest rate, $p_{m,t} M_t$ represents resource revenue from ownership of resource-extracting firms, $w_{h,t}$ is the wage rate of high-skilled labor, $w_{l,t}$ is the wage rate of low-skilled labor, $\tau_{L,t}$ is the labor-income tax rate used to finance subsidies for R&D in both new-variety innovation and resource-substituting technology development, and T_t is the lump-sum tax or transfer determined by environmental tax policies.

From standard dynamic optimization, the Euler equation is given by

$$\frac{\dot{c}_t}{c_t} = r_t - \rho. \tag{26}$$

2.7 Government

The government implements two balanced-budget policies: one to subsidize R&D in new-variety innovation and resource-substituting technology development, and another involving environmental taxation.[11]

The budget constraint associated with subsidies for new-variety innovation and resource-substituting technology development is given by

$$\tau_{L,t}\left(w_{h,t}+w_{l,t}L\right)=sw_{h,t}H_{n,t}+\sigma w_{h,t}H_{R,t}. \tag{27}$$

Since $s\in[0,1)$ and $\sigma\in[0,1)$, households pay a labor-income tax to finance these R&D subsidies.

The budget constraint associated with environmental taxation is given by

$$(\tau_t-1)p_{m,t}M_t=T_t, \tag{28}$$

where $\tau_t=\tau_0 e^{g_\tau t}$. If the government subsidizes resource use in production at time t (i.e., $\tau_t\leq 1$), households pay a lump-sum tax to finance the subsidy (i.e., $T_t\leq 0$). Conversely, if the government taxes resource use in production at time t (i.e., $\tau_t>1$), households receive a lump-sum transfer financed by environmental tax revenues (i.e., $T_t>0$).[12] Although it would be more natural for the government to issue public debt and use environmental tax revenues collected at one point in time to finance resource-use subsidies or lump-sum transfers at another point in time, introducing public debt would substantially complicate the dynamic analysis of the model. Therefore, to maintain tractability, we assume that the environmental-tax policy satisfies a balanced-budget condition at each point in time.

[11] Assuming two independent balanced-budget policies greatly simplifies the analysis and enables us to isolate and compare the effects of subsidies for new-variety innovation and resource-substituting technology development while accounting for the interaction between these subsidies and environmental policy.

[12] For example, suppose that the present value of transfers to households is non-negative at time 0; that is, $TR_0\equiv\int_0^\infty T_\tau e^{-\int_0^\tau r_u\,du}\,d\tau\geq 0$, and that the environmental tax becomes less stringent over time (i.e., $g_\tau<0$). In this case, resource use is initially taxed, generating revenue that is rebated to households through lump-sum transfers. As the tax rate gradually declines, the policy eventually turns into a subsidy for resource use, which must be financed through lump-sum taxation of households in later periods.

2.8 Equilibrium Conditions and Aggregate Economy

The final-goods market clears according to $y_t = c_t$. The asset-market-clearing condition is given by $a_t = v_{R,t}n_{R,t} + v_{M,t}n_{M,t}$. Using (17), (20), and $\theta_t \equiv n_{R,t}/n_t$, the evolution of θ_t is given by

$$\dot{\theta}_t = \alpha_t(1-\theta_t) - \lambda_t\theta_t, \tag{29}$$

which indicates that the share of resource-substituting firms, θ_t, can be interpreted as a stock that depreciates as new varieties are introduced. In particular, since the growth rate of product varieties is given by $g_{n,t} = \lambda_t$, a higher intensity of resource-substituting innovation, $\alpha_t(1-\theta_t)$, is required to increase θ_t when it is already high.

From (7), (9), (11), (13), $p_{M,t} = \mu a_M \tau_t p_{m,t}$, and $p_{R,t} = \mu a_R w_{l,t}$, the shares of income accruing to material resources and low-skilled labor are

$$\tau_t p_{m,t} M_t = \frac{(1-\theta_t)y_t}{\mu}, \tag{30}$$

and

$$w_{l,t}L = \frac{\theta_t y_t}{\mu}, \tag{31}$$

respectively, while the remaining share, $(\mu-1)/\mu$, accrues to monopolistic profits, which in turn determine the demand for high-skilled labor through (19) and (22).

Given the level of resource extraction, $M_t = \frac{(1-\theta_t)y_t}{\mu\tau_t p_{m,t}}$, and using the Hotelling rule in (2), the assumption $g_{\tau,t} = g_\tau$, and the Euler equation $\dot{y}_t/y_t = r_t - \rho$, the growth rate of resource extraction is given by

$$g_{M,t} \equiv \frac{\dot{M}_t}{M_t} = -\left[\frac{\theta_t}{1-\theta_t}g_{\theta,t} + \rho + g_\tau\right] \equiv -\hat{g}_{M,t}, \tag{32}$$

where $g_{\theta,t} \equiv \dot{\theta}_t/\theta_t$. Ceteris paribus, an increase in the share of resource-substituting firms (i.e., $g_{\theta,t} > 0$) increases the rate of decline in resource extraction, $\hat{g}_{M,t}$, because the prospect of lower future resource demand induces resource-producing firms to bring extraction forward, thereby increasing current extraction and accelerating resource depletion.[13]

The transversality condition implies that the initial level of resource extraction, M_0, is determined so as to satisfy the resource-exhaustion condition. Consequently, the path of resource extraction is given by

$$M_0 = \frac{S_0}{\int_0^\infty e^{-\int_0^t \hat{g}_{M,u}\,du}\,dt}, \qquad M_t = M_0 e^{-\int_0^t \hat{g}_{M,u}\,du}. \tag{33}$$

Note that the rate of decline in resource extraction, $\hat{g}_{M,t}$, and, in particular, the growth rate of the resource tax, g_τ, affect not only the path of resource extraction but also its initial level, M_0. Since $\frac{\partial}{\partial g_\tau}\left[e^{-\int_0^t \hat{g}_{M,u}\,du}\right] < 0$, a lower tax-growth rate, g_τ, reduces the initial level of resource extraction, M_0, while increasing resource extraction in later periods. This more gradual extraction path preserves the resource stock and thereby mitigates the environmental externality associated with resource use, as shown below. Equation (33) also shows that changes in the initial tax level, τ_0, affect neither resource allocation nor the extraction path, implying that τ_0 is dynamically neutral (e.g., Grimaud and Rougé, 2005, 2014; Daubanes and Grimaud, 2010; Pittel and Bretschger, 2010; Tabata, 2026).[14] Therefore, the analysis that follows focuses on variations in the tax-growth rate, g_τ, rather than on the initial tax level, τ_0.

Moreover, substituting (6), (9), (10), and (13) into (4) yields the following Cobb–Douglas aggregate production function:

$$y_t = A n_t^{\kappa-1}\left(\frac{M_t}{a_M(1-\theta_t)}\right)^{1-\theta_t}\left(\frac{L}{a_R\theta_t}\right)^{\theta_t}, \tag{34}$$

where θ_t determines the relative intensities of material-resource and labor inputs in aggregate production.

Thus, the output growth rate is given by

$$g_{y,t} = \frac{\dot{y}_t}{y_t} = (\kappa-1)g_{n,t} + \theta_t \ln\left(\frac{L/(a_R\theta_t)}{M_t/[a_M(1-\theta_t)]}\right)g_{\theta,t} - (1-\theta_t)\hat{g}_{M,t}. \tag{35}$$

[13]This effect, whereby policies that promote alternatives to fossil fuels increase current fossil-fuel extraction and use, is known as the "Green Paradox" (e.g., Sinn, 2008; van der Ploeg and Withagen, 2015; van der Meijden and Smulders, 2017).

[14]This result is well known in the literature. A higher initial tax level permanently reduces resource demand by a constant factor, but it does not affect the intertemporal arbitrage condition faced by resource-producing firms. Consequently, changes in τ_0 have no effect on either resource allocation or the extraction path.

The output growth rate, $g_{y,t}$, is driven by (i) new-variety growth, $g_{n,t}$, (ii) changes in the composition of production through θ_t, and (iii) variations in the rate of resource extraction, $\hat{g}_{M,t}$. A higher rate of decline in resource extraction, $\hat{g}_{M,t}$, reduces output growth, while a larger share of resource-substituting firms, θ_t, mitigates this negative effect through channel (iii). The effect of θ_t on $g_{y,t}$ through channel (ii), however, depends on whether $\frac{L}{a_R\theta_t} > \frac{M_t}{a_M(1-\theta_t)}$ holds.[15]

3 Steady-State Equilibrium

This section derives the steady-state equilibrium in which the share of resource-substituting firms, θ_t, remains constant over time, and examines the effects of subsidies for R&D in new varieties and resource-substituting technology development, as well as environmental taxation, on long-run economic growth and welfare.

3.1 Steady-State Properties

To examine the dynamic properties of the model, we define $V_{R,t} \equiv \frac{y_t}{v_{R,t}n_{R,t}}$ and $V_{M,t} \equiv \frac{y_t}{v_{M,t}n_{M,t}}$. Appendix B shows that the model's dynamics are fully characterized by the evolution of θ_t, $V_{R,t}$, and $V_{M,t}$. Moreover, given an initial value θ_0, numerical analysis shows that the economy follows a saddle-path trajectory that converges monotonically to a unique steady-state equilibrium under plausible parameter values. In what follows, we omit the time subscript t for variables that are constant in the steady state.

Since $V_{M,t}$, $V_{R,t}$, and θ_t are constant in the steady state, we have $\frac{\dot{v}_{M,t}}{v_{M,t}} = \frac{\dot{v}_{R,t}}{v_{R,t}} = g_y - g_n$. Substituting these expressions into (15) and (16), and using (8), (12), the Euler equation $\dot{y}_t/y_t = r - \rho$, and $g_n = \lambda$, we obtain the balanced-growth values of $v_{M,t}$ and $v_{R,t}$ as

$$v_{M,t} = \frac{\pi_{M,t}}{\rho + \lambda + \alpha} = \frac{\mu - 1}{\mu}\frac{y_t}{n_t}\frac{1}{\rho + \varphi H_n^{\psi} + \phi H_R^{\psi}}, \tag{36}$$

[15]Since the initial tax level, τ_0, does not affect the path of resource extraction, it does not affect the output growth rate, $g_{y,t}$, either.

$$v_{R,t} = \frac{\pi_{R,t}}{\rho + \lambda} = \frac{\mu - 1}{\mu} \frac{y_t}{n_t} \frac{1}{\rho + \varphi H_n^{\psi}}, \tag{37}$$

where we have used (18) and (21) to derive these expressions.

Substituting (36) and (37) into (19) and (22) yields

$$\frac{\varphi}{\phi(1-\theta)} \frac{\rho + \lambda}{\rho + \alpha + \lambda} = \frac{1-s}{1-\sigma} \left(\frac{H_n}{H_R} \right)^{1-\psi}.$$

From (29), noting that $\theta = \frac{\alpha}{\lambda + \alpha}$ in the steady state, this condition can be rewritten as

$$\frac{1-\sigma}{1-s} \left[\frac{\varphi}{\phi} + \left(\frac{1-H_n}{H_n} \right)^{\psi} \right] = \left(\frac{H_n}{1-H_n} \right)^{1-\psi} + \left(\frac{H_n}{1-H_n} \right)^{1-2\psi} \frac{\phi}{\rho / H_n^{\psi} + \varphi}. \tag{38}$$

Equation (38) determines the steady-state equilibrium level of skilled labor, H_n, allocated to new-variety innovation. As shown in Appendix C, if we assume $\psi \leq \frac{\rho + \phi}{\rho + 2\phi} \in \left(\frac{1}{2}, 1 \right)$, then the right-hand side of (38) is increasing in H_n, whereas the left-hand side is decreasing in H_n. Therefore, as illustrated in Figure 1, there exists a unique steady-state equilibrium allocation of skilled labor between new-variety innovation, H_n, and resource-substituting technology development, $H_R = 1 - H_n$.

[Figure 1 about here.]

Moreover, since the left-hand side of (38) increases with s but decreases with σ, the steady-state allocation of high-skilled labor to new-variety innovation, $H_n(s, \sigma)$, is increasing in the subsidy rate for variety R&D, s, and decreasing in the subsidy rate for resource-substituting technology development, σ. Conversely, the steady-state allocation of high-skilled labor to resource-substituting technology development, $H_R(s, \sigma)$, is increasing in σ and decreasing in s.

As shown in Appendix C, the environmental-policy parameters, (τ_0, g_τ), do not affect the dynamics of θ_t, $V_{R,t}$, or $V_{M,t}$. Consequently, they do not affect the allocations of high-skilled labor, $H_{n,t}$ and $H_{R,t}$, or the resulting variety growth rate, $g_{n,t}$, either in the steady-state equilibrium or along the transition path. Therefore, the resource-tax growth rate, g_τ, affects economic growth, $g_{y,t}$, only through its impact on the rate of resource extraction, $\hat{g}_{M,t}$, as explained above.

3.2 Economic Growth

From (17), the steady-state variety growth rate is given by

$$g_n(s,\sigma) = \lambda = \varphi \left[H_n(s,\sigma)\right]^{\psi}, \tag{39}$$

which is increasing in s and decreasing in σ.

From (29), the steady-state share of resource-substituting firms is

$$\theta(s,\sigma) = \frac{\alpha}{\lambda + \alpha} = \frac{\phi \left[H_R(s,\sigma)\right]^{\psi}}{\varphi \left[H_n(s,\sigma)\right]^{\psi} + \phi \left[H_R(s,\sigma)\right]^{\psi}}, \tag{40}$$

which is increasing in σ and decreasing in s.

From (32) and (35), and noting that $g_{\theta,t} = 0$ in the steady state, the steady-state output growth rate is given by

$$g_y(s,\sigma,g_\tau) = (\kappa - 1) g_n(s,\sigma) - \left[1 - \theta(s,\sigma)\right](\rho + g_\tau), \tag{41}$$

where $\rho + g_\tau$ denotes the steady-state rate of decline in resource extraction (i.e., $\hat{g}_M = \rho + g_\tau$), capturing the negative effect of resource scarcity on economic growth. In what follows, we assume that the parameter condition $(\kappa - 1)\varphi > \rho + g_\tau$ holds, which ensures that $g_y > 0$ when $H_n = 1$.

Differentiating $g_y(s, \sigma, g_\tau)$ with respect to s and σ yields

$$\frac{\partial g_y}{\partial s} = (\kappa - 1) \underbrace{\frac{\partial g_n}{\partial s}}_{(+)} + \underbrace{\frac{\partial \theta}{\partial s}}_{(-)} (\rho + g_\tau), \tag{42}$$

$$\frac{\partial g_y}{\partial \sigma} = (\kappa - 1) \underbrace{\frac{\partial g_n}{\partial \sigma}}_{(-)} + \underbrace{\frac{\partial \theta}{\partial \sigma}}_{(+)} (\rho + g_\tau). \tag{43}$$

Equation (42) implies that a higher subsidy rate for variety R&D, s, raises output growth g_y through faster variety growth g_n, but lowers it by reducing θ, thereby increasing the weight of resource extraction in the growth equation. Conversely, equation (43) implies that a higher subsidy rate for resource-substituting technology development, σ, lowers g_y through reduced variety growth, but raises it by increasing θ, thereby mitigating the negative impact of resource extraction on economic growth.

Moreover, differentiating $g_y(s, \sigma, g_\tau)$ with respect to g_τ yields

$$\frac{\partial g_y}{\partial g_\tau} = -(1 - \theta) < 0. \tag{44}$$

Equation (44) implies that a lower resource-tax growth rate, g_τ, increases output growth, g_y, by reducing the rate of decline in resource extraction, $\rho + g_\tau$, and thereby alleviating resource scarcity.

Proposition 1 summarizes these results.

Proposition 1. Consider the steady-state equilibrium.

(i) An increase in the subsidy rate for variety R&D, s, raises the variety growth rate, g_n, and reduces the share of resource-substituting firms, θ.

(ii) An increase in the subsidy rate for resource-substituting technology development, σ, raises θ and reduces g_n.

(iii) The effects of s and σ on the steady-state output growth rate, g_y, are ambiguous. A higher s increases

g_y through faster variety growth but reduces it through greater reliance on material-resource-based production. Conversely, a higher σ reduces g_y through slower variety growth but increases it by mitigating the negative impact of resource extraction.

(iv) A lower resource-tax growth rate, g_τ, increases output growth, g_y, by reducing the rate of decline in resource extraction, $\rho + g_\tau$, thereby alleviating the negative effect of resource scarcity on economic growth.

3.3 Welfare

We now examine the effects of subsidies for new-variety innovation, s, resource-substituting technology development, σ, and the resource-tax growth rate, g_τ, on steady-state welfare.[16]

As shown in Appendix D, the lifetime utility of a representative household is given by

$$\rho U = \ln c_0 + \frac{g_y}{\rho} - \omega\rho\Omega_z, \tag{45}$$

where

$$c_0 = An_0^{\kappa-1}\left[\frac{(\rho+g_\tau)S_0}{a_M(1-\theta)}\right]^{1-\theta}\left[\frac{L}{a_R\theta}\right]^{\theta},$$

$$\Omega_z \equiv \int_0^\infty e^{-\rho t}Z_t\,dt = \frac{\eta S_0(\rho+g_\tau)}{(\delta+\rho)(2\rho+g_\tau)},$$

and Ω_z denotes aggregate pollution, defined as the present discounted value of pollution damages. Since the rate of decline in resource extraction is constant in the steady-state equilibrium, i.e., $\hat{g}_M = \rho + g_\tau$, steady-state aggregate pollution, Ω_z, is independent of s and σ. In contrast, since $\frac{\partial\Omega_z}{\partial g_\tau} = \frac{\rho\eta S_0}{(\delta+\rho)(2\rho+g_\tau)^2} > 0$, a lower resource-tax growth rate, g_τ, reduces steady-state aggregate pollution, Ω_z, because it slows the pace

[16] Since the initial tax level, τ_0, affects neither the path of resource extraction nor the output growth rate, $g_{y,t}$, it has no effect on the lifetime utility of the representative household. This reflects the well-known rent-tax property of natural-resource taxation. However, once the representative-household assumption is relaxed, the distribution of resource rents between resource owners and the government depends on the level of τ_0 and on the government's redistribution policy. Consequently, changes in τ_0 may have important distributional implications even though they do not affect aggregate efficiency (e.g., Tabata, 2026).

of resource extraction, thereby reducing cumulative pollution and mitigating the associated environmental externality.

We first examine the effects of s and σ on steady-state welfare, U. Differentiating U with respect to s and σ yields

$$\rho \frac{dU}{ds} = \underbrace{\ln\left[\frac{L/(a_R\theta)}{(\rho+g_\tau)S_0/[a_M(1-\theta)]}\right] \underbrace{\frac{\partial\theta}{\partial s}}_{(-)}}_{\frac{1}{c_0}\frac{\partial c_0}{\partial\theta}\frac{\partial\theta}{\partial s}} + \underbrace{\frac{1}{\rho}\left[(\kappa-1)\underbrace{\frac{\partial g_n}{\partial s}}_{(+)} + \underbrace{\frac{\partial\theta}{\partial s}}_{(-)}(\rho+g_\tau)\right]}_{\frac{\partial g_y}{\partial s}}, \tag{46}$$

$$\rho \frac{dU}{d\sigma} = \underbrace{\ln\left[\frac{L/(a_R\theta)}{(\rho+g_\tau)S_0/[a_M(1-\theta)]}\right] \underbrace{\frac{\partial\theta}{\partial \sigma}}_{(+)}}_{\frac{1}{c_0}\frac{\partial c_0}{\partial\theta}\frac{\partial\theta}{\partial \sigma}} + \underbrace{\frac{1}{\rho}\left[(\kappa-1)\underbrace{\frac{\partial g_n}{\partial \sigma}}_{(-)} + \underbrace{\frac{\partial\theta}{\partial \sigma}}_{(+)}(\rho+g_\tau)\right]}_{\frac{\partial g_y}{\partial \sigma}}, \tag{47}$$

The first terms in (46) and (47) capture the effects of the subsidy rate for variety R&D, s, and the subsidy rate for resource-substituting technology development, σ, on welfare through the initial level of consumption, c_0. The sign of these terms depends on whether $\frac{L}{a_R\theta} > \frac{(\rho+g_\tau)S_0}{a_M(1-\theta)}$ holds.

Suppose that $\frac{L}{a_R\theta} > \frac{(\rho+g_\tau)S_0}{a_M(1-\theta)}$, implying a relatively resource-poor economy. Then, the first term in (46) is negative, whereas the first term in (47) is positive. This is because, in such an economy, a higher subsidy rate for variety R&D, s, increases resource intensity and thereby reduces the initial level of consumption, whereas a higher subsidy rate for resource-substituting technology development, σ, reduces resource intensity and thereby increases the initial level of consumption.

Conversely, suppose that $\frac{L}{a_R\theta} < \frac{(\rho+g_\tau)S_0}{a_M(1-\theta)}$, implying a relatively resource-rich economy. Then, the first term in (46) is positive, whereas the first term in (47) is negative. This is because, in such an economy, a higher s increases resource intensity and thereby increases the initial level of consumption, whereas a higher σ reduces resource intensity and thereby decreases the initial level of consumption. These results highlight that the welfare effects of subsidies operating through the initial level of consumption, c_0, depend crucially on both the relative abundance of resources and the existing resource intensity of the economy, as reflected in θ.

The second terms in (46) and (47) capture the effects of the subsidy rates for variety R&D, s, and resource-substituting technology development, σ, on welfare through the output growth rate, g_y. As analyzed in Section 3.2, since the effects of s and σ on the steady-state output growth rate are ambiguous, the signs of the second terms are also generally ambiguous.

In particular, a higher s affects output growth through two opposing channels. On the one hand, it increases g_y by stimulating variety growth, which enhances productivity through the expansion of input variety. On the other hand, it reduces g_y by lowering the share of resource-substituting firms, θ, thereby increasing dependence on material resources and amplifying the negative impact of resource extraction. The net effect of s on welfare through the growth channel depends on the relative strength of these opposing effects.

Similarly, a higher σ also operates through two opposing channels. On the one hand, it reduces g_y by diverting skilled labor away from variety innovation and toward resource-substituting innovation, thereby slowing variety growth. On the other hand, it increases g_y by raising the share of resource-substituting firms, θ, which reduces dependence on material resources and mitigates the negative impact of resource extraction.

Overall, the effects of subsidies for new-variety innovation, s, and resource-substituting technology development, σ, on steady-state welfare are generally ambiguous. They depend on the relative abundance of the initial natural-resource stock, S_0, compared with the supply of low-skilled labor, L, as well as on the existing resource intensity of the economy, $1 - \theta$, which is itself determined by the relative efficiency of variety innovation and resource-substituting technology development.

We next examine the effect of g_τ on steady-state welfare, U. Differentiating U with respect to g_τ yields

$$\rho \frac{dU}{dg_\tau} = \underbrace{\frac{1-\theta}{\rho + g_\tau}}_{\frac{1}{c_0}\frac{\partial c_0}{\partial g_\tau}} - \underbrace{\frac{1-\theta}{\rho}}_{-\frac{\partial g_y}{\partial g_\tau}} - \omega\rho \underbrace{\frac{\rho\eta S_0}{(\delta+\rho)(2\rho+g_\tau)^2}}_{\frac{\partial \Omega_z}{\partial g_\tau}}, \tag{48}$$

Since $\frac{\partial c_0}{\partial g_\tau} > 0$, $\frac{\partial g_y}{\partial g_\tau} < 0$ and $\frac{\partial \Omega_z}{\partial g_\tau} > 0$, the first term in (48) is positive, whereas the second and third terms are negative. Consequently, the effect of the resource-tax growth rate, g_τ, on steady-state welfare is ambiguous. Intuitively, a lower g_τ reduces the initial level of resource extraction, $M_0 = (\rho + g_\tau)S_0$, and thus the initial level of consumption, c_0, lowering welfare. At the same time, it increases output growth, g_y, and reduces aggregate pollution, Ω_z, both of which improve welfare. Therefore, the overall welfare effect of g_τ depends on the relative strength of these opposing effects.

To further examine the growth and welfare effects of subsidies for new-variety innovation, s, and resource-substituting technology development, σ, as well as the role of environmental policy in shaping these effects, the next section presents a numerical analysis of the model.

4 Numerical Analysis

To gain further insight into the growth and welfare effects of subsidies for new-variety innovation and resource-substituting technology development, as well as the role of environmental policy in shaping these effects, this section presents numerical simulations of the model. Given the stylized nature of the framework, the simulations are intended to complement the theoretical analysis rather than identify precise optimal subsidy rates. Section 4.1 describes the parameterization, Section 4.2 examines steady-state effects, and Section 4.3 analyzes transitional effects.

[Table 1 about here.]

4.1 Model Parameterization

Table 1 summarizes the parameter values used in the calibration. Following Chu et al. (2023), we set the discount rate to $\rho = 0.05$ and normalize the productivity parameter in the final-good sector (A), the productivity parameters in the resource-using and resource-substituting sectors (a_M and a_R), the pollution-awareness parameter (ω), the pollution flow per unit of resource use (η), and the initial number of intermediate goods (n_0) to unity. To compare economies with different resource endowments, we consider both a relatively resource-rich economy ($S_0 = 4$) and a relatively resource-poor economy ($S_0 = 1$). We also vary the initial endowment of natural resources from 0.3 to 4 to assess the robustness of the welfare implications of R&D subsidy policies. The price-regulation (patent-breadth) parameter, μ, is set to 1.3, implying a markup consistent with the estimates reported by Britton et al. (2000) and Galí et al. (2007).

The supply of low-skilled labor is set to $L = 3.4215$ so that the benchmark skill premium, measured by w_h/w_l, equals 1.5. Combining (19), (31), and (36) yields the steady-state skill premium[17]

$$\frac{w_h}{w_l} = \frac{\varphi(\mu - 1)L}{(1 - s)H_n^{1-\psi}} \frac{1}{\theta(\rho + \lambda + \alpha)}.$$

This calibration is consistent with the average earnings premium of tertiary-educated workers relative to individuals with upper-secondary education across OECD countries (OECD, 2025).

The parameter κ captures the positive productivity externalities associated with the expansion of input varieties. Its closest empirical counterpart is the elasticity of productivity with respect to variety estimated by Broda et al. (2006), which ranges from 1.05 to 1.20. However, because these estimates are derived from international trade data, they do not fully capture the productivity externalities from variety expansion considered in this paper. Following Brunnschweiler et al. (2021), we adopt a conservative calibration and set the benchmark value of κ at the lower bound of the empirical range, namely $\kappa = 1.05$.

There is no consensus in the empirical literature regarding the contribution of natural resources to

[17] Along the transition path, defining $V_{M,t} \equiv y_t/(v_{M,t} n_{M,t})$, the skill premium is given by

$$\frac{w_{h,t}}{w_{l,t}} = \frac{\varphi(\mu - 1)L}{(1 - s)H_{n,t}^{1-\psi}} \frac{1}{\theta_t(1 - \theta_t)V_{M,t}}.$$

production. Estimates of the output elasticity of energy alone range from approximately 0.03 to 0.20 (see Stern, 2011, for a survey), illustrating the considerable uncertainty surrounding the productive role of natural resources. While many energy and climate-economy models assume values between 0.05 and 0.10, Stern (2000) and Kümmel et al. (2002) argue that the output elasticity of energy substantially exceeds its cost share. Given that the present theoretical framework is intended to capture not only resource-poor economies but also resource-rich economies, we calibrate the productivity parameter for resource-substituting technology development, ϕ, and the innovation-productivity parameter, φ, such that benchmark steady-state resource intensity, $1-\theta=\frac{\lambda}{\lambda+\alpha}$, equals 0.2 and the steady-state output growth rate, $g_y=(\kappa-1)g_n-(1-\theta)\rho=0.02$, matches the long-run growth rate of U.S. per capita GDP. This calibration yields $\phi=2.7045$ and $\varphi=1.31$.

Although many countries have raised fossil-fuel and emissions taxes, environmentally related tax revenues have remained relatively stable over the past two decades. According to OECD (2024), the average ratio of such revenues to GDP in OECD countries declined from 1.81% in 2000 to 1.5% in 2020. Complex tax structures and offsetting subsidies often neutralize the effect of higher tax rates. Based on this discussion and our ad valorem tax framework, we set the benchmark resource-tax growth rate to $g_\tau=0$ and consider values ranging from -0.03 to 0, focusing on declining tax-growth-rate paths as commonly assumed in the literature.

According to IPCC (2014), only about half of carbon emissions accumulate in the atmosphere. While taking this empirical evidence into account, we adopt a more conservative calibration. Specifically, we normalize the pollution flow per unit of resource use to $\eta=1$ and set the pollution depreciation rate to $\delta=0.02$. Under this specification, aggregate pollution corresponds to approximately 71.43% of the hypothetical pollution stock that would prevail in the absence of pollution depreciation.[18] This calibration is also consistent with the parameter restriction $\rho+g_\tau\geq\delta$ imposed in Appendix D.

Given that the United States and many other OECD countries do not differentiate R&D support between new-variety innovation and resource-substituting technology development, we consider symmetric

[18] From (45), setting $\delta=g_\tau=0$ yields $\Omega_z|_{\delta=g_\tau=0}=\frac{\eta S_0}{2\rho}$.
Since $\rho=0.05$ and $\delta=0.02$, it follows that $\frac{\Omega_z}{\Omega_z|_{\delta=g_\tau=0}}=\frac{\rho}{\rho+\delta}\simeq 0.7143$.

subsidies as a natural benchmark and set $s = \sigma$. According to the OECD R&D Tax Incentives Database, the implied R&D tax subsidy rate for OECD countries in 2020 was approximately 20% for small firms and 17% for large firms. Based on these figures, we set $s = \sigma = 0.2$.

4.2 Steady State

This subsection examines the growth and welfare effects of subsidies for new-variety innovation and resource-substituting technology development in the steady-state equilibrium. Section 4.2.1 analyzes the effects of changes in the subsidy rate for variety R&D, s, whereas Section 4.2.2 examines the corresponding effects of changes in the subsidy rate for resource-substituting technology development, σ. As implied by equations (46) and (47), the welfare effects of R&D subsidy policies depend on the initial endowment of natural resources, S_0. We therefore consider both a relatively resource-rich economy ($S_0 = 4$) and a relatively resource-poor economy ($S_0 = 1$).

4.2.1 Effects of Subsidies for New-Variety Innovation

Figure 2 illustrates the steady-state effects of changes in the subsidy rate for variety R&D, s, from 0 to 0.5 under different values of the resource-tax growth rate, g_τ. Panels (a)–(h) show the variety growth rate, g_n; the share of resource-substituting firms, θ; the output growth rate, g_y; the skill premium, w_h/w_l; aggregate pollution in resource-rich economies, Ω_z ($S_0 = 4$); welfare gains in resource-rich economies, ΔU ($S_0 = 4$); aggregate pollution in resource-poor economies, Ω_z ($S_0 = 1$); and welfare gains in resource-poor economies, ΔU ($S_0 = 1$), respectively. Solid lines represent the benchmark case ($g_\tau = 0$), while dashed and dash-dotted lines correspond to $g_\tau = -0.015$ and $g_\tau = -0.03$, respectively. A lower g_τ implies a more stringent environmental policy, as it slows resource extraction and reduces pollution.

As implied by equation (45), differences in the initial endowment of natural resources, S_0, affect welfare in resource-rich and resource-poor economies through differences in the initial level of consumption, c_0, and aggregate pollution, Ω_z. However, all other equilibrium macroeconomic variables take the same values in the two economies. The welfare gains reported in Figures 2(f) and 2(h) are measured in consumption-equivalent terms, that is, as the equivalent percentage increase in initial consumption resulting from a change in the subsidy rate for new-variety innovation, s, from its benchmark value of 0.2.[19]

[Figure 2 about here.]

Consistent with Proposition 1(i), a higher subsidy rate for variety R&D, s, raises the variety growth rate, g_n (Figure 2(a)) and lowers the share of resource-substituting firms, θ (Figure 2(b)). Under our benchmark parameter values, the existing share of resource-substituting firms, θ, is already high, implying that the economy's resource intensity is relatively low. As a result, the positive effect of s on g_y through faster variety growth dominates its negative effect on g_y through the greater reliance on resource-based production associated with a lower θ. Consequently, as shown in Figure 2(c), a higher subsidy rate for variety R&D raises the output growth rate, g_y.

A higher subsidy rate for variety R&D, s, also increases the demand for high-skilled labor relative to that for low-skilled labor, thereby raising the skill premium, w_h/w_l, through conditions (19) and (22) (Figure 2(d)). As explained above, the rate of decline in resource extraction is independent of s in the steady-state equilibrium, i.e., $\hat{g}_M = \rho + g_\tau$. Therefore, steady-state aggregate pollution, Ω_z, is independent of s (Figures 2(e) and 2(g)). Nevertheless, the level of aggregate pollution is higher in resource-rich economies ($S_0 = 4$) than in resource-poor economies ($S_0 = 1$), since equation (45) implies that Ω_z increases with the initial resource endowment, S_0.

Figures 2(f) and 2(h) show that the effect of s on welfare gains, ΔU, differs markedly between resource-rich and resource-poor economies. In resource-rich economies ($S_0 = 4$), a marginal increase in the subsidy rate for variety R&D, s, above its benchmark value of 0.2 raises welfare. Under the benchmark environmental policy ($g_\tau = 0$), welfare gains reach a maximum at approximately $s = 0.4$, after which further increases in s reduce welfare gains. By contrast, in resource-poor economies ($S_0 = 1$), a marginal increase in s lowers welfare, and the associated welfare loss becomes larger as s increases. As shown in equation (46), the effect of s on welfare through the initial level of consumption, c_0, is positive when $\frac{L}{a_R \theta} < \frac{(\rho + g_\tau) S_0}{a_M (1-\theta)}$,

[19] Welfare gains in Figures 2–3, 5–6, and 8–9 are measured in consumption-equivalent terms. For each value of s or σ, we first compute the corresponding welfare level, U_s or U_σ. We then determine the level of initial consumption that, holding g_y and Ω_z fixed at their benchmark values under $s = \sigma = 0.2$, yields the same welfare level. The reported welfare gain is the percentage difference between this consumption level and its benchmark value under $s = \sigma = 0.2$.

a condition more likely to hold in resource-rich than in resource-poor economies. Consequently, a marginal increase in s raises welfare in resource-rich economies. By contrast, in resource-poor economies, the negative effect of s through c_0 dominates its positive effect through the higher output growth rate, g_y, implying that welfare falls as s increases.

Figure 2 further shows that the resource-tax growth rate, g_τ, does not affect the steady-state values of g_n, θ, or w_h/w_l, since the environmental-policy parameters, (τ_0, g_τ), leave the dynamics of θ_t, $V_{R,t}$, and $V_{M,t}$ unchanged. Consistent with Proposition 1(iv), a lower resource-tax growth rate, g_τ, increases output growth, g_y (Figure 2(c)), and reduces aggregate pollution, Ω_z (Figures 2(e) and 2(g)), by lowering the rate of decline in resource extraction, $\rho + g_\tau$, thereby alleviating resource scarcity and its associated environmental externality. Moreover, Figures 2(f) and 2(h) show that, as g_τ declines and environmental policy becomes more stringent, the welfare gains from a higher subsidy rate for variety R&D diminish in resource-rich economies ($S_0 = 4$), while the corresponding welfare losses become larger in resource-poor economies ($S_0 = 1$). Intuitively, a lower g_τ already delivers higher output growth, reducing the additional growth benefits generated by a higher s. Furthermore, because the condition $\frac{L}{a_R\theta} < \frac{(\rho+g_\tau)S_0}{a_M(1-\theta)}$ is less likely to hold when g_τ is lower, the positive effect of s on welfare through the initial level of consumption, c_0, also becomes weaker. Consequently, in resource-rich economies, the welfare-maximizing subsidy rate for variety R&D decreases as g_τ falls.

4.2.2 Effects of Subsidies for Resource-Substituting Technology Development

Figure 3 illustrates the effects of changes in the subsidy rate for resource-substituting technology development, σ, in both resource-rich ($S_0 = 4$) and resource-poor ($S_0 = 1$) economies. The welfare gains reported in Figures 3(f) and 3(h) are also measured in consumption-equivalent terms, following the same methodology as in Figures 2(f) and 2(h).

[Figure 3 about here.]

Consistent with Proposition 1(ii), a higher subsidy rate for resource-substituting technology development, σ, lowers the variety growth rate, g_n (Figure 3(a)) and increases the share of resource-substituting firms, θ (Figure 3(b)). Under our benchmark parameter values, the negative effect of slower variety growth dominates the positive effect of lower resource dependence. Consequently, a higher σ lowers the output growth rate, g_y (Figure 3(c)).

While a higher subsidy rate for resource-substituting technology development, σ, increases the demand for both high- and low-skilled labor by promoting the adoption of resource-substituting technology, the effect on low-skilled wages is modest because the economy is already relatively labor-intensive under our benchmark parameter values. Consequently, the skill premium, w_h/w_l, rises (Figure 3(d)). Moreover, since the rate of decline in resource extraction is independent of σ in the steady-state equilibrium, i.e., $\hat{g}_M = \rho + g_\tau$, aggregate pollution, Ω_z, is likewise unaffected by σ (Figures 3(e) and 3(g)). However, aggregate pollution is higher in resource-rich economies ($S_0 = 4$) than in resource-poor economies ($S_0 = 1$), reflecting their larger initial endowment of natural resources.

Figures 3(f) and 3(h) show that the effect of σ on welfare gains, ΔU, differs substantially between resource-rich and resource-poor economies. Its implications are the reverse of those of the variety-R&D subsidy, s: a higher σ tends to lower welfare in resource-rich economies but raise welfare in resource-poor economies. Within the range of σ values considered in our sensitivity analysis, welfare falls monotonically with σ in resource-rich economies, whereas it rises monotonically in resource-poor economies. As shown in equation (47), the effect of σ on welfare through the initial level of consumption, c_0, is positive when $\frac{L}{a_R\theta} > \frac{(\rho+g_\tau)S_0}{a_M(1-\theta)}$, a condition more likely to hold in resource-poor than in resource-rich economies. Consequently, the negative consumption effect dominates in resource-rich economies, so that welfare falls as σ increases. By contrast, in resource-poor economies, the positive effect through c_0 outweighs the negative effect through the lower output growth rate, g_y, implying that welfare gains increase with σ.

Figure 3 also shows that the resource-tax growth rate, g_τ, does not affect the steady-state values of g_n, θ, or w_h/w_l, because the environmental-policy parameters, (τ_0, g_τ), do not affect the dynamics of θ_t, $V_{R,t}$, or $V_{M,t}$. Consistent with Proposition 1(iv), a lower g_τ increases output growth, g_y (Figure 3(c)), and reduces aggregate pollution, Ω_z (Figures 3(e) and 3(g)), by lowering the rate of decline in resource extraction, $\rho + g_\tau$. Figures 3(f) and 3(h) further show that, as g_τ declines and environmental policy becomes more stringent, the welfare loss from a higher subsidy rate for resource-substituting technology development becomes smaller in resource-rich economies ($S_0 = 4$), while the corresponding welfare gains become larger in resource-poor economies ($S_0 = 1$). Intuitively, a lower g_τ already delivers higher output growth, reducing the additional growth losses associated with a higher σ. Furthermore, because the condition $\frac{L}{a_R\theta} > \frac{(\rho+g_\tau)S_0}{a_M(1-\theta)}$ is more likely to hold when g_τ is lower, the positive effect of σ on welfare through the initial level of consumption, c_0, also becomes larger. Consequently, welfare losses decline in resource-rich economies, whereas welfare gains increase in resource-poor economies.

4.3 Transitional Dynamics

In this subsection, we use the relaxation algorithm of Trimborn et al. (2008) to analyze the transitional dynamics following changes in R&D subsidy policies. We compare the steady-state and transitional effects of these policies and examine how environmental policy shapes their implications. Section 4.3.1 examines the effects of an increase in the subsidy rate for variety R&D, s, whereas Section 4.3.2 considers an increase in the subsidy rate for resource-substituting technology development, σ.

4.3.1 Dynamic Effects of the Variety R&D Subsidy

Figure 4 illustrates the transitional effects of raising the subsidy rate for variety R&D, s, from 0.2 to 0.4 in resource-rich economies ($S_0 = 4$) under the benchmark environmental policy ($g_\tau = 0$). Panels (a)–(g) show the dynamics of the variety growth rate, $g_{n,t}$, the share of resource-substituting firms, θ_t, the output growth rate, $g_{y,t}$, the skill premium, $w_{h,t}/w_{l,t}$, the log level of consumption, $\log(c_t)$, the growth rate of resource extraction, $g_{M,t}$, and the level of resource extraction, M_t, respectively. Solid lines represent the transitional dynamics, while dashed and dash-dotted lines denote the Old BGP ($s = 0.2$) and New BGP ($s = 0.4$), respectively. Note that the steady-state values of M_t and $g_{M,t}$ are identical under the two BGPs, since the rate of decline in resource extraction is independent of s in the steady state, i.e., $\hat{g}_M = \rho + g_\tau$.

[Figure 4 about here.]

A higher subsidy rate for variety R&D, s, raises the variety growth rate, $g_{n,t}$ (Figure 4(a)), with the initial increase exceeding the long-run increase. As shown in Figure 4(b), the share of resource-substituting firms, θ_t—and hence the labor intensity of the economy—gradually declines toward its lower steady-state level under the New BGP ($s = 0.4$). This reallocates high-skilled labor toward new-variety R&D, contributing to the overshooting of $g_{n,t}$ and the initial decline in the skill premium, $w_{h,t}/w_{l,t}$ (Figure 4(d)). However, the gradual decline in labor intensity decreases the relative demand for low-skilled labor, causing the skill premium to rise over time. Consequently, the skill premium under the New BGP eventually exceeds that under the Old BGP. Moreover, the anticipated decline in θ_t, implying higher future resource intensity, increases expected future resource demand. Anticipating this change, resource-extracting firms postpone extraction, slowing the pace of resource extraction during the transition (Figure 4(f)). As a result, current resource extraction, M_t, falls below its steady-state level, while future extraction slightly exceeds it (Figure 4(g)).

As shown in equation (35), the output growth rate, $g_{y,t}$, is driven by (i) product-variety growth, $g_{n,t}$, (ii) changes in production composition through θ_t, and (iii) variations in the rate of resource extraction, $\hat{g}_{M,t}$. Following the increase in the subsidy rate for variety R&D, $g_{n,t}$ rises (Figure 4(a)), while θ_t declines (Figure 4(b)). At the same time, the anticipated increase in future resource demand induces resource-extracting firms to postpone extraction, lowering the rate of decline in resource extraction, $\hat{g}_{M,t}$ (Figure 4(f)). The increase in $g_{n,t}$ raises output growth through channel (i). In a resource-rich economy ($S_0 = 4$), where $\frac{L}{a_R\theta} < \frac{M_t}{a_M(1-\theta)}$, is likely to hold, the decline in θ_t also raises output growth through channel (ii). In addition, the lower rate of decline in resource extraction raises output growth through channel (iii). At the same time, the decline in θ_t increases reliance on resource-based production, exerting a negative effect through channel (iii). As shown in Figure 4(c), the positive effects dominate this negative effect, so that $g_{y,t}$ increases. Moreover, the initial increase in $g_{y,t}$ exceeds its long-run increase, reflecting the temporary overshooting of $g_{n,t}$ shown in Figure 4(a).

Figure 4(e) shows that the log level of consumption gradually converges to its New-BGP level ($s = 0.4$). The New-BGP consumption path is steeper than the Old-BGP path ($s = 0.2$) because output growth is higher under the New BGP. However, its initial consumption level is lower due to households' optimal intertemporal allocation of resources. The transition path initially lies above the New-BGP path, reflecting higher lifetime income generated by temporarily higher output growth during the transition, a shift toward a more resource-conserving extraction path, and the gradual shift in the production structure toward greater resource intensity. Since output growth rapidly converges to its New-BGP value (Figure 4(c)), the slope of the consumption path quickly converges as well. Thereafter, the log level of consumption gradually converges to its New-BGP level.

As shown in Figures 4(f) and 4(g), the subsidy rate for variety R&D, s, affects the transition paths of resource extraction and, therefore, aggregate pollution, Ω_z. Moreover, because key endogenous variables such as $g_{y,t}$ and θ_t evolve differently during the transition than in the steady state, the welfare effects of changes in s may differ from those implied by the steady-state analysis. Figure 5 compares the transitional and steady-state effects of s on aggregate pollution, Ω_z, and welfare gains, ΔU, under the benchmark environmental policy ($g_\tau = 0$) for different initial resource endowments, S_0. Solid and dashed lines represent the transitional and steady-state effects, respectively. For $S_0 = 4$, the dashed lines in Figures 5(a) and 5(b) reproduce the results represented by the solid lines in Figures 2(e) and 2(f), respectively. Likewise, for $S_0 = 1$, the dashed lines in Figures 5(c) and 5(d) reproduce the results represented by the solid lines in Figures 2(g) and 2(h), respectively.

[Figure 5 about here.]

Since Figure 4 examines the resource-rich case ($S_0 = 4$), we begin with the corresponding results in Figures 5(a) and 5(b). Figure 5(a) shows that, once transitional dynamics are taken into account, a marginal increase in the subsidy rate for variety R&D, s, above its benchmark value of 0.2 reduces aggregate pollution, Ω_z. As shown in Figure 4(g), the decline in θ_t increases expected future resource demand, inducing resource-extracting firms to postpone extraction. Consequently, resource extraction is shifted from the present to the future, lowering the present discounted value of pollution damages. Similar results hold for all values of S_0 considered in Figure 5 (Figures 5(a), 5(c), and 5(e)).

Figure 5(b) further shows that accounting for transitional dynamics amplifies the welfare gains from an increase in the subsidy rate for variety R&D, s, relative to the steady-state prediction. This result is driven by two factors. First, the consumption path initially lies above the New-BGP path because temporarily higher output growth, a more resource-conserving extraction path, and a shift in production toward greater resource intensity increase lifetime income (Figure 4(e)). Second, aggregate pollution, Ω_z, is lower than in the corresponding steady-state equilibrium (Figure 5(a)). Figure 5(d) further shows that, once transitional dynamics are taken into account, an increase in the subsidy rate for variety R&D, s, improves welfare even in resource-poor economies ($S_0 = 1$), where the steady-state analysis predicts that a higher subsidy rate would reduce welfare. However, as shown in Figure 5(f) for the more resource-poor economy with $S_0 = 0.3$, the qualitative steady-state result remains unchanged even when transitional dynamics are taken into account. In this economy, a marginal increase in the subsidy rate for variety R&D, s, continues to reduce welfare. Even so, the magnitude of the welfare loss becomes smaller once transitional dynamics are taken into account, as higher initial consumption and lower aggregate pollution both contribute positively to welfare.

[Figure 6 about here.]

Finally, Figure 6 illustrates how the transitional welfare effects of the subsidy rate for variety R&D, s, vary with the resource-tax growth rate, g_τ. The solid lines represent the benchmark case ($g_\tau = 0$) and reproduce the solid lines in Figures 5(b), 5(d), and 5(f), while the dashed and dash-dotted lines correspond to $g_\tau = -0.015$ and $g_\tau = -0.03$, respectively. Consistent with the steady-state welfare effects of s shown in Figures 2(f) and 2(h), Figures 6(a)–6(c) show that, even when transitional dynamics are taken into account, a decline in g_τ and the resulting increase in environmental-policy stringency reduce the welfare gains from a higher subsidy rate for variety R&D in resource-rich economies ($S_0 = 4$) and resource-poor economies ($S_0 = 1$), while increasing the corresponding welfare losses in more resource-poor economies ($S_0 = 0.3$). Intuitively, in addition to the two channels identified in the steady-state analysis, a lower g_τ provides resource-extracting firms with a stronger incentive to postpone extraction by increasing expected future resource demand. As a result, the additional postponement of resource extraction induced by a marginal increase in s becomes smaller, reducing the associated decline in pollution and the resulting welfare gains. Consequently, the welfare-enhancing effect of s through transitional dynamics becomes weaker.

Summarizing these numerical results for changes in the subsidy rate for variety R&D, s, we obtain the following proposition.

Proposition 2. The numerical simulations yield the following results.

(i) An increase in the subsidy rate for variety R&D, s, is more likely to improve welfare in resource-rich economies than in resource-poor economies.

(ii) Accounting for transitional dynamics makes an increase in the subsidy rate for variety R&D, s, more welfare-enhancing because it raises consumption through temporarily higher output growth, a more resource-conserving extraction path, and a shift in production toward greater resource intensity, while also reducing the present discounted value of pollution damages.

(iii) A decline in the resource-tax growth rate, g_τ, and the resulting increase in environmental-policy stringency reduce the welfare-enhancing effect of the subsidy rate for variety R&D, s, because they already provide higher output growth and a more resource-conserving extraction path, thereby reducing the additional growth, consumption, and environmental benefits generated by a marginal increase in s.

4.3.2 Dynamic Effects of Resource-Substituting Technology Development Subsidy

Figure 7 illustrates the transitional effects of increasing the subsidy rate for resource-substituting technology development, σ, from 0.2 to 0.4 in resource-poor economies ($S_0 = 1$) under the benchmark environmental policy ($g_\tau = 0$). As in Figure 4, solid lines represent the transitional dynamics, while dashed and dash-dotted lines denote the Old BGP ($\sigma = 0.2$) and New BGP ($\sigma = 0.4$), respectively. Consistent with the steady-state analysis, the values of M_t and $g_{M,t}$ are unchanged across the two BGPs because the rate of decline in resource extraction is independent of σ, i.e., $\hat{g}_M = \rho + g_\tau$.

[Figure 7 about here.]

A higher subsidy rate for resource-substituting technology development, σ, decreases the variety growth rate, $g_{n,t}$ (Figure 7(a)), with the initial decline exceeding the long-run decrease. As shown in Figure 7(b), the share of resource-substituting firms, θ_t—and hence the labor intensity of the economy—gradually increases toward its higher steady-state level under the New BGP ($\sigma = 0.4$). This reallocates high-skilled labor toward resource-substituting technology development, contributing to the initial decline in $g_{n,t}$ and the initial surge in the skill premium, $w_{h,t}/w_{l,t}$ (Figure 7(d)). However, the gradual increase in labor intensity raises the relative demand for low-skilled labor, causing the skill premium to decline over time. Consequently, the skill premium gradually converges to its New-BGP level, which remains above that under the Old BGP. Note that, although increases in both s and σ raise the skill premium in the long run, their short-run effects differ. An increase in σ initially raises the skill premium, whereas an increase in s initially lowers it, owing to the different transitional responses of $V_{M,t}$ and $V_{R,t}$. Moreover, the anticipated increase in θ_t, implying lower future resource intensity, reduces expected future resource demand. Anticipating this change, resource-extracting firms accelerate resource extraction, thereby increasing the pace of extraction during the transition (Figure 7(f)). As a result, current resource extraction, M_t, exceeds its steady-state level, while future extraction falls slightly below it (Figure 7(g)).

From equation (35), the output growth rate, $g_{y,t}$, is driven by (i) product-variety growth, $g_{n,t}$, (ii) changes in production composition through θ_t, and (iii) variations in the rate of resource extraction, $\hat{g}_{M,t}$. Following the increase in the subsidy rate for resource-substituting technology development, σ, the variety growth rate, $g_{n,t}$, declines (Figure 7(a)), while θ_t rises (Figure 7(b)). At the same time, the anticipated decline in future resource demand induces resource-extracting firms to accelerate extraction, increasing the rate of decline in resource extraction, $\hat{g}_{M,t}$ (Figure 7(f)). The decline in $g_{n,t}$ reduces output growth through channel (i). In addition, the higher rate of decline in resource extraction lowers output growth through channel (iii). By contrast, in a resource-poor economy ($S_0 = 1$), where $\frac{L}{a_R\theta} > \frac{M_t}{a_M(1-\theta)}$, is likely to hold, the increase in θ_t raises output growth through channel (ii). Moreover, the increase in θ_t reduces reliance on resource-based production, exerting a positive effect through channel (iii). As shown in Figure 7(c), the two negative effects dominate the two positive effects, so that $g_{y,t}$ declines. The initial decline in $g_{y,t}$ reflects both the sharp fall in $g_{n,t}$ through channel (i) (Figure 7(a)) and the increase in the rate of decline in resource extraction, $\hat{g}_{M,t}$, through channel (iii) (Figure 7(f)). Thereafter, $g_{y,t}$ gradually converges to its New-BGP level as the positive effect of a higher θ_t diminishes as θ_t approaches its steady-state value.

Figure 7(e) shows that the log level of consumption gradually converges to its New-BGP level ($\sigma = 0.4$). The New-BGP consumption path is flatter than the Old-BGP path ($\sigma = 0.2$) because output growth is lower under the New BGP. However, its initial consumption level is higher due to households' optimal intertemporal allocation of resources. The transition path initially lies below the New-BGP path, reflecting the reduction in lifetime income associated with the shift toward a more resource-intensive extraction path and the gradual shift in the production structure toward greater labor intensity. Since output growth steadily converges to its New-BGP value (Figure 7(c)), the slope of the consumption path also converges steadily. Thereafter, the log level of consumption gradually converges to its New-BGP level.

Figure 8 compares the transitional and steady-state effects of σ on aggregate pollution, Ω_z, and welfare, U, under the benchmark environmental policy ($g_\tau = 0$) for different initial resource endowments, S_0. Solid and dashed lines represent the transitional and steady-state effects, respectively. For $S_0 = 4$, the dashed lines in Figures 8(a) and 8(b) reproduce the results represented by the solid lines in Figures 3(e) and 3(f), while for $S_0 = 1$, those in Figures 8(c) and 8(d) reproduce the results represented by the solid lines in Figures 3(g) and 3(h).

[Figure 8 about here.]

Since Figure 7 examines the resource-poor case ($S_0 = 1$), we begin with Figures 8(c) and 8(d). Figure 8(c) shows that, once transitional dynamics are taken into account, a marginal increase in the subsidy rate for resource-substituting technology development, σ, above its benchmark value of 0.2 increases aggregate pollution, Ω_z, opposite to the effect of a higher subsidy rate for variety R&D, s, shown in Figures 5(a), 5(c), and 5(e). As shown in Figure 7(g), the increase in θ_t reduces expected future resource demand, inducing resource-extracting firms to accelerate extraction. Consequently, resource extraction is higher in the initial periods and lower in later periods than along the steady-state path, increasing the present discounted value of pollution damages. Similar results hold for all values of S_0 considered in Figure 8 (Figures 8(a), 8(c), and 8(e)).

Figure 8(d) further shows that, once transitional dynamics are taken into account, an increase in the subsidy rate for resource-substituting technology development, σ, reduces welfare even in resource-poor economies ($S_0 = 1$), where the steady-state analysis predicts that a higher subsidy rate would increase welfare. Thus, accounting for transitional dynamics reverses the steady-state welfare implication. Two factors drive this result. First, the consumption path initially lies below the New-BGP path because a more resource-intensive extraction path and a shift in production toward greater labor intensity reduce lifetime income (Figure 7(e)). Second, aggregate pollution, Ω_z, is higher than in the corresponding steady-state equilibrium (Figure 8(c)). However, as shown in Figure 8(f) for the more resource-poor economy with $S_0 = 0.3$, the qualitative steady-state result remains unchanged even when transitional dynamics are taken into account. In this economy, a marginal increase in the subsidy rate for resource-substituting technology development, σ, continues to improve welfare. Even so, the magnitude of the welfare gain becomes smaller once transitional dynamics are taken into account, as lower initial consumption and higher aggregate pollution both reduce welfare.

[Figure 9 about here.]

Finally, Figure 9 illustrates how the transitional welfare effects of the subsidy rate for resource-substituting technology development, σ, vary with the resource-tax growth rate, g_τ. The solid lines represent the benchmark case ($g_\tau = 0$) and reproduce the solid lines in Figures 8(b), 8(d), and 8(f), while the dashed and dash-dotted lines correspond to $g_\tau = -0.015$ and $g_\tau = -0.03$, respectively. Consistent with the steady-state welfare effects of σ shown in Figures 3(f) and 3(h), Figures 9(a)–9(c) show that, even when transitional dynamics are taken into account, a decline in g_τ and the resulting increase in environmental-policy stringency reduce the welfare losses from a higher subsidy rate for resource-substituting technology development, σ, in resource-rich economies ($S_0 = 4$) and resource-poor economies ($S_0 = 1$), while increasing the corresponding welfare gains in more resource-poor economies ($S_0 = 0.3$). Intuitively, in addition to the two channels identified in the steady-state analysis, a lower g_τ provides resource-extracting firms with a stronger incentive to postpone extraction by increasing expected future resource demand. As a result, the additional pollution generated by a marginal increase in σ becomes smaller, reducing its adverse welfare effects. Consequently, the welfare implications of a higher σ become more favorable when environmental policy is more stringent.

Summarizing these numerical results for changes in the subsidy rate for resource-substituting technology development, σ, we obtain the following proposition.

Proposition 3. The numerical simulations yield the following results.

(i) An increase in the subsidy rate for resource-substituting technology development, σ, is more likely to improve welfare in resource-poor economies than in resource-rich economies.

(ii) Accounting for transitional dynamics worsens the welfare implications of an increase in the subsidy rate for resource-substituting technology development, σ, because it lowers consumption through a more resource-intensive extraction path and a shift in production toward greater labor intensity, while also increasing the present discounted value of pollution damages.

(iii) A decline in the resource-tax growth rate, g_τ, and the resulting increase in environmental-policy stringency increase the welfare-enhancing effect of the subsidy rate for resource-substituting technology development, σ, because they already provide higher output growth and a more resource-conserving extraction path, thereby reducing the additional growth, consumption, and environmental costs associated with a marginal increase in σ.

5 Concluding Remarks

This paper has introduced endogenous resource-substituting technology development into a variety-expanding endogenous growth model with polluting non-renewable resources. The analysis has highlighted a trade-off between new-variety innovation and resource-substituting technology development. We have shown that subsidies for new-variety R&D promote growth but increase resource dependence, whereas subsidies for resource-substituting technology development have the opposite effects. We have further demonstrated that the welfare effects of these policies depend on natural-resource endowments and environmental policy. In particular, subsidies for new-variety innovation are more likely to improve welfare in resource-rich economies, whereas subsidies for resource-substituting technology development are more beneficial in resource-poor economies. Moreover, stricter environmental policies strengthen the welfare gains from subsidies for resource-substituting technology development and weaken those from subsidies for new-variety R&D. These findings suggest that innovation and environmental policies should be designed jointly, taking into account resource endowments and the interactions among technological change, resource use, and pollution.

To keep the analysis tractable and to highlight the key economic mechanisms, we have employed a stylized R&D-based growth model with several simplifying assumptions. While these assumptions facilitate analytical transparency and yield intuitive insights, they also impose certain limitations. Before concluding, we briefly discuss these limitations and suggest several directions for future research.

First, we focus on the case where the resource tax follows the simple path $\tau_t = \tau_0 e^{g_\tau t}$, and do not analyze the optimal combination of environmental taxation and R&D subsidies. In general, however, the first-best Pigouvian tax may exhibit a more complex time profile. An important direction for future research is to characterize the socially optimal allocation and the optimal joint design of environmental and innovation policies within the present framework. In particular, analyzing optimal R&D subsidies under both first-best and second-best environmental-policy regimes would provide further insights into the interaction between innovation and environmental policies.

Second, the paper does not consider differences across tasks in the feasibility of adopting resource-substituting technologies. While this assumption helps highlight the trade-off between new-variety innovation and resource-substituting technology development, future research could incorporate task heterogeneity to provide a richer characterization of the transition from resource-based production to resource-substituting technologies and its implications for growth, resource dependence, and welfare.

Third, for analytical simplicity, we consider a closed-economy framework and abstract from transboundary pollution. Since the differences in the welfare effects of R&D policies between resource-rich and resource-poor economies partly depend on this assumption, extending the model to a multi-country setting would be a promising direction for future research. In particular, it would be interesting to examine the welfare implications and optimal design of R&D policies under alternative trade regimes and to explore how international pollution spillovers affect the interaction among innovation, resource use, and welfare.

Finally, our numerical results should be interpreted with caution. The finding that subsidies for new-variety R&D promote growth and improve welfare over a broad range of initial resource endowments depends on the benchmark parameterization, which assumes a high share of resource-substituting firms and relatively low resource intensity. Moreover, for analytical tractability, the model assumes that all new varieties of intermediate goods are initially produced using resource-intensive technologies, a simplifying assumption for which direct empirical support is limited. As a result, the calibration relies on specific parameter assumptions, and the numerical simulations should be viewed primarily as illustrations of the model's theoretical mechanisms rather than as precise quantitative policy recommendations. Examining the robustness of the results under alternative assumptions and calibrations remains an important avenue for future research.

Appendix

A Appendix A

In the steady-state equilibrium, since θ_t is constant and $y_t = c_t$, it follows from (26) and (31) that the low-skilled wage $w_{l,t}$ grows at the output growth rate, $g_y = r - \rho$. Meanwhile, the resource price $p_{m,t}$ grows at the interest rate r according to the Hotelling rule in equation (2). Because the resource tax grows at the constant rate $g_{\tau,t} = g_\tau > -\rho$, the after-tax resource price, $\tau_t p_{m,t}$, grows faster than the low-skilled wage. Consequently, condition (14) holds for a broad range of parameter values.

B Appendix B

This appendix describes the dynamics of the economy. Using (8), (12), (15), and (16), together with the definitions $V_{R,t} \equiv \frac{y_t}{v_{R,t} n_{R,t}}$ and $V_{M,t} \equiv \frac{y_t}{v_{M,t} n_{M,t}}$, we obtain $\frac{\dot{v}_{R,t}}{v_{R,t}} = r_t - \frac{\mu-1}{\mu} V_{R,t}\theta_t$, $\frac{\dot{v}_{M,t}}{v_{M,t}} = r_t + \alpha_t - \frac{\mu-1}{\mu} V_{M,t}(1-\theta_t)$.

Combining the above equations with (17), (20), and (26) yields

$$\dot{V}_{R,t} = \left[-\rho + \frac{\mu-1}{\mu} V_{R,t}\theta_t - \alpha_t \frac{1-\theta_t}{\theta_t} \right] V_{R,t}, \tag{A1}$$

$$\dot{V}_{M,t} = \left[-\rho + \frac{\mu-1}{\mu} V_{M,t}(1-\theta_t) - \frac{\lambda_t}{1-\theta_t} \right] V_{M,t}. \tag{A2}$$

Using the free-entry conditions (19) and (22) together with the definitions of $V_{M,t}$ and $V_{R,t}$, we obtain

$$\frac{\varphi}{\phi} \frac{\theta_t}{(1-\theta_t)^2} \frac{V_{R,t}}{V_{M,t}} = \frac{1-s}{1-\sigma} \left(\frac{H_{n,t}}{1-H_{n,t}} \right)^{1-\psi} \quad \Leftrightarrow \quad H_{n,t} = \frac{\left[\frac{(1-\sigma)\varphi}{(1-s)\phi} \frac{\theta_t}{(1-\theta_t)^2} \frac{V_{R,t}}{V_{M,t}} \right]^{\frac{1}{1-\psi}}}{1 + \left[\frac{(1-\sigma)\varphi}{(1-s)\phi} \frac{\theta_t}{(1-\theta_t)^2} \frac{V_{R,t}}{V_{M,t}} \right]^{\frac{1}{1-\psi}}}, \tag{A3}$$

Equation (A3) shows that $H_{n,t}$ can be expressed as a function of θ_t, $V_{M,t}$, and $V_{R,t}$, that is, $H_{n,t} = H_n(\theta_t, V_{M,t}, V_{R,t})$. Noting that $\lambda_t = \varphi H_{n,t}^{\psi}$ and $\alpha_t = \phi(1-H_{n,t})^{\psi}$, both λ_t and α_t can also be expressed as functions of θ_t, $V_{M,t}$, and $V_{R,t}$.

Hence, the dynamic properties of the model are fully characterized by the evolution of θ_t, $V_{R,t}$, and $V_{M,t}$ using (29), (A1), (A2), and (A3). By linearizing the system around the steady state and examining the eigenvalues of the Jacobian matrix, we can characterize the local dynamics of the model. Since θ_t is the state variable, whereas $V_{R,t}$ and $V_{M,t}$ are jump variables, given an initial value $\theta_0 = \frac{n_{R,0}}{n_0}$, if one eigenvalue is negative and the other two are positive, the system exhibits saddle-path stability.

Numerical analysis under the benchmark parameter values shows that the eigenvalues are −5.6132, 0.37179, and 3.0349. Therefore, the steady state is saddle-path stable, and the economy converges monotonically to a unique steady-state equilibrium under plausible parameter values.

C Appendix C

By differentiating the right-hand side of (38) with respect to H_n, we obtain

$$\frac{\partial RHS}{\partial H_n} = \frac{1}{(1-H_n)^2}\left(\frac{1-H_n}{H_n}\right)^{\psi}\left[\frac{\psi\rho\phi(1-H_n)^{1+\psi}}{(\rho+\varphi H_n^{\psi})^2} + 1 - \psi - (2\psi-1)\frac{\phi(1-H_n)^{\psi}}{\rho+\varphi H_n^{\psi}}\right]. \tag{A4}$$

Now suppose that

$$1-\psi-(2\psi-1)\frac{\phi(1-H_n)^{\psi}}{\rho+\varphi H_n^{\psi}} > 1-\psi-\frac{\phi(2\psi-1)}{\rho} > 0,$$

or equivalently, $\psi \leq \frac{\rho+\phi}{\rho+2\phi}$. Then, it follows that $\frac{\partial RHS}{\partial H_n} > 0$. Thus, the condition $\psi \leq \frac{\rho+\phi}{\rho+2\phi}$ is sufficient for the right-hand side of (38) to be increasing in H_n.

D Appendix D

Since $c_t = y_t$, we have $c_t = c_0 e^{g_y t}$. Substituting this into $\int_0^\infty e^{-\rho t}\ln c_t\, dt$ and rearranging yields $\frac{1}{\rho}\ln c_0 + \frac{1}{\rho^2}g_y$. Since $\hat{g}_M = \rho + g_\tau$, it follows that $M_\tau = M_0 e^{-(\rho+g_\tau)\tau}$. Using (33), we obtain $M_\tau = (\rho+g_\tau)S_0 e^{-(\rho+g_\tau)\tau}$. Assuming $\hat{g}_M = \rho + g_\tau \geq \delta$, substituting this into $Z_t = \eta\int_0^t M_\tau e^{-\delta(t-\tau)}d\tau$ yields

$$Z_t = \eta(\rho+g_\tau)S_0\frac{e^{-\delta t}-e^{-\rho t}}{\rho+g_\tau-\delta}, \tag{A5}$$

Substituting (A5) into $\Omega_z \equiv \int_0^\infty e^{-\rho t}Z_t\, dt$ yields $\Omega_z = \frac{\eta S_0(\rho+g_\tau)}{(\delta+\rho)(2\rho+g_\tau)}$.

Table 1: Benchmark Parameter Values

Parameter	Description	Value
ρ	Discount rate	0.05
A	Productivity level in the final-good sector	1
a_M	Productivity parameter in the material-resource-using sector	1
a_R	Productivity parameter in the resource-substituting sector	1
ω	Pollution awareness parameter	1
η	Pollution per unit of resource use	1
n_0	Initial number of varieties	1
S_0	Initial resource stock	1 or 4
μ	Patent-breadth parameter	1.3
L	Supply of low-skilled labor	3.4215
κ	Productivity externalities from input-variety expansion	1.05
ϕ	Resource-substituting technology development productivity parameter	2.7045
φ	Variety-innovation productivity parameter	1.31
g_τ	Resource-tax growth rate	0
δ	Pollution depreciation rate	0.02
s	Subsidy rate for variety R&D	0.2
σ	Subsidy rate for resource-substituting technology development	0.2

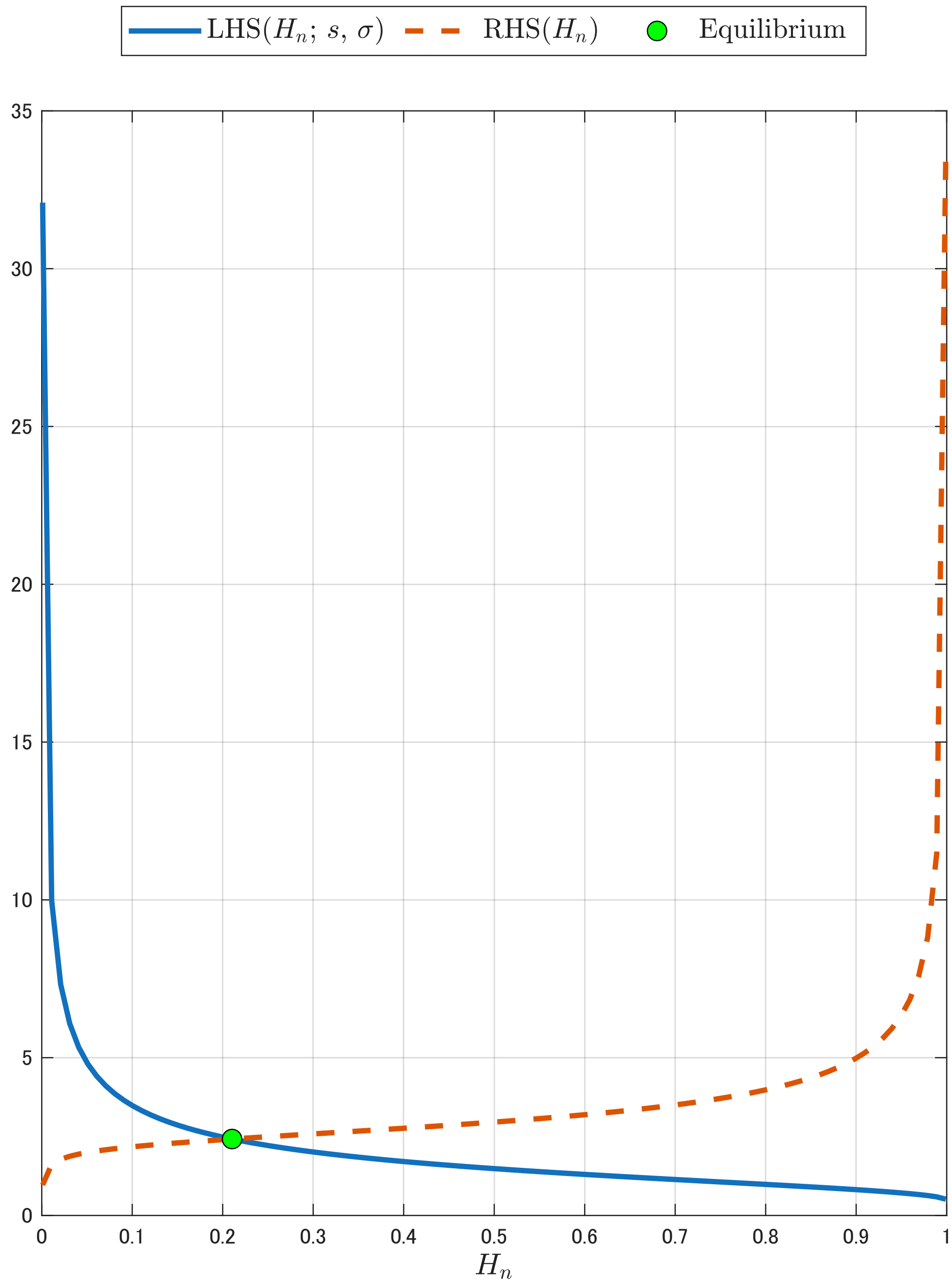

Figure 1: Steady-State Equilibrium Allocation of Skilled Labor to Variety R&D

Notes: An increase in the subsidy rate for variety R&D (s) shifts the LHS curve upward, whereas an increase in the subsidy rate for resource-substituting technology development (σ) shifts the LHS curve downward.

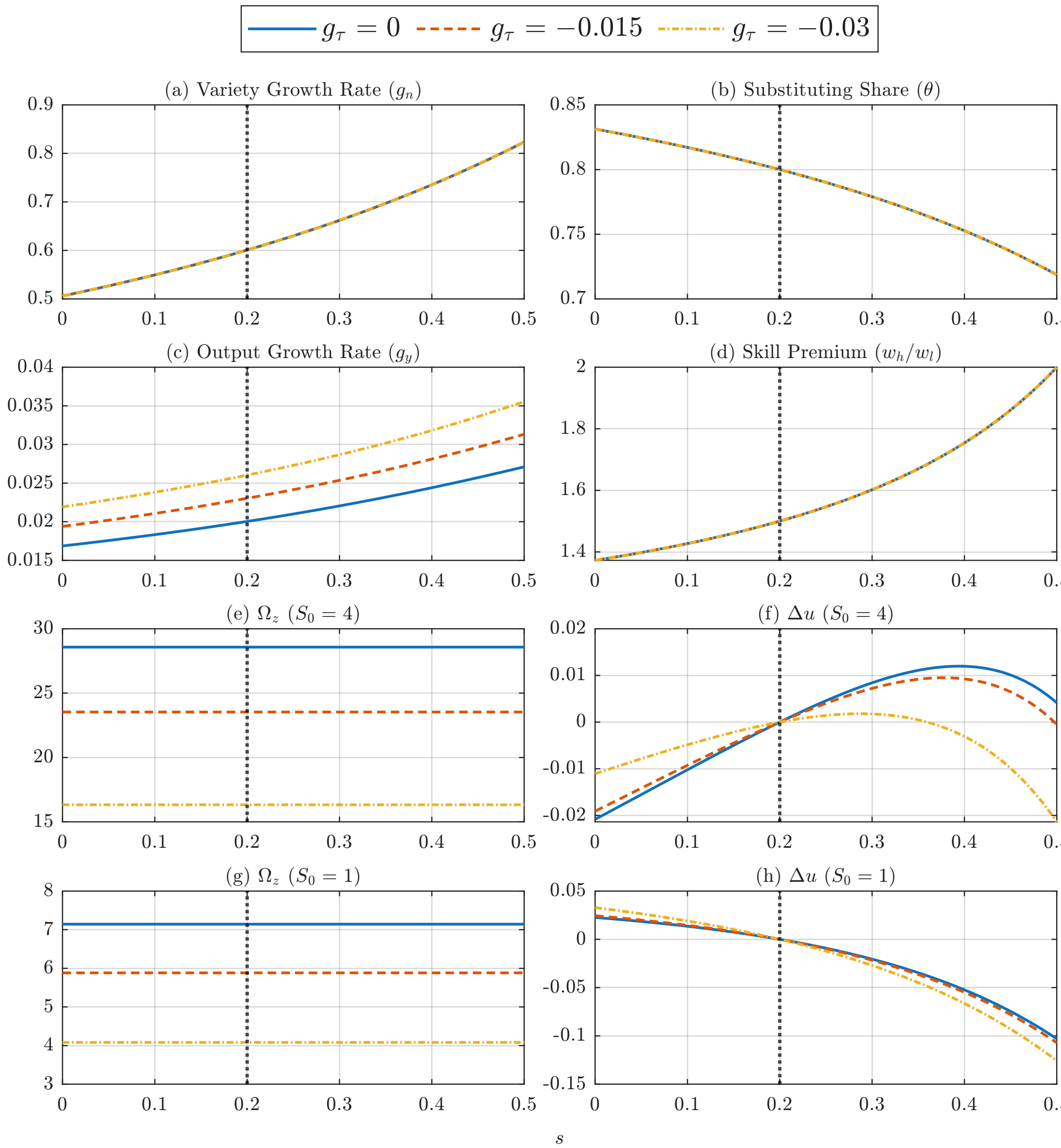

Figure 2: Effects of the Variety R&D Subsidy Rate (s)

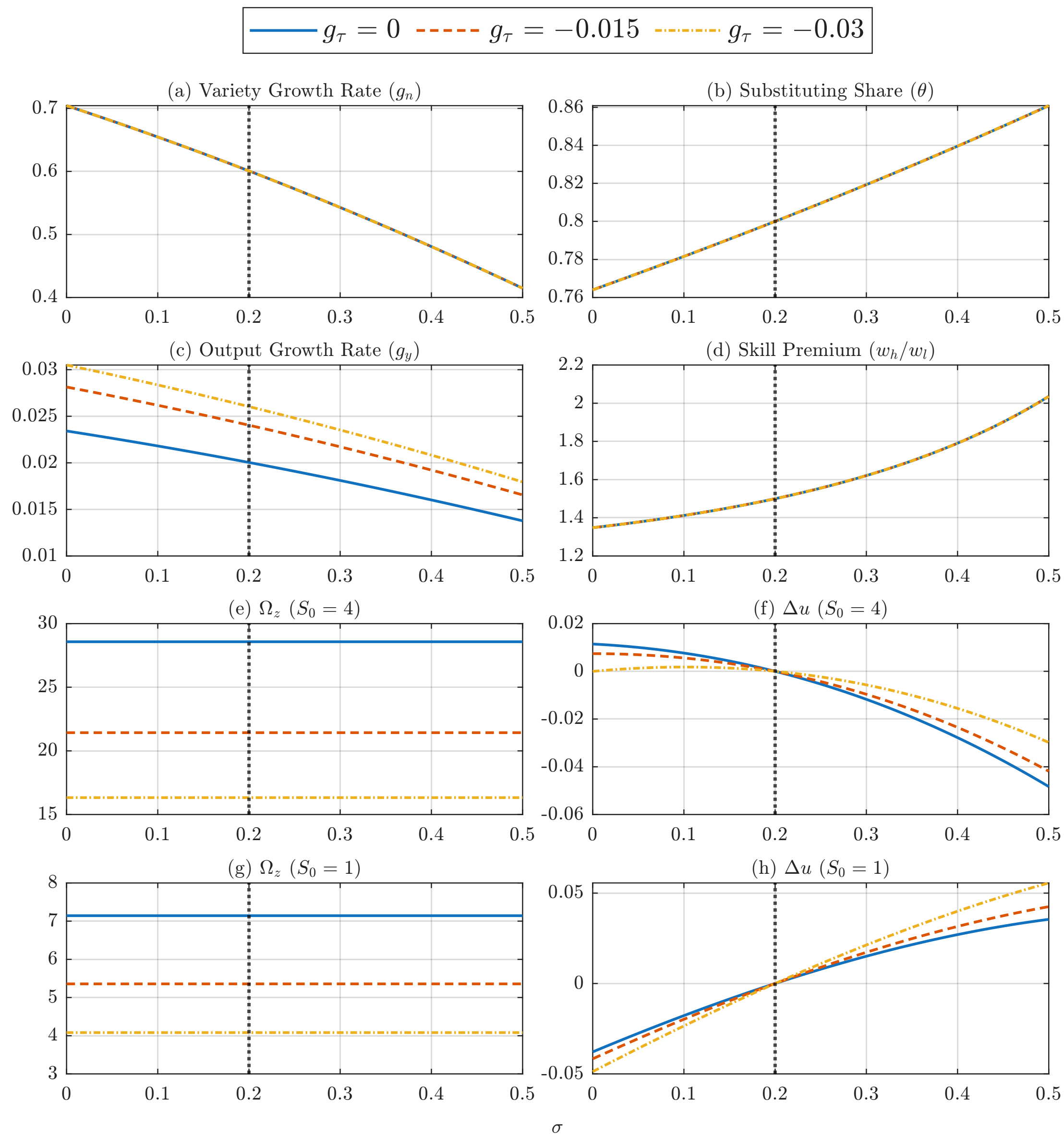

Figure 3: Effects of the Resource-Substituting Technology Development Subsidy Rate (σ)

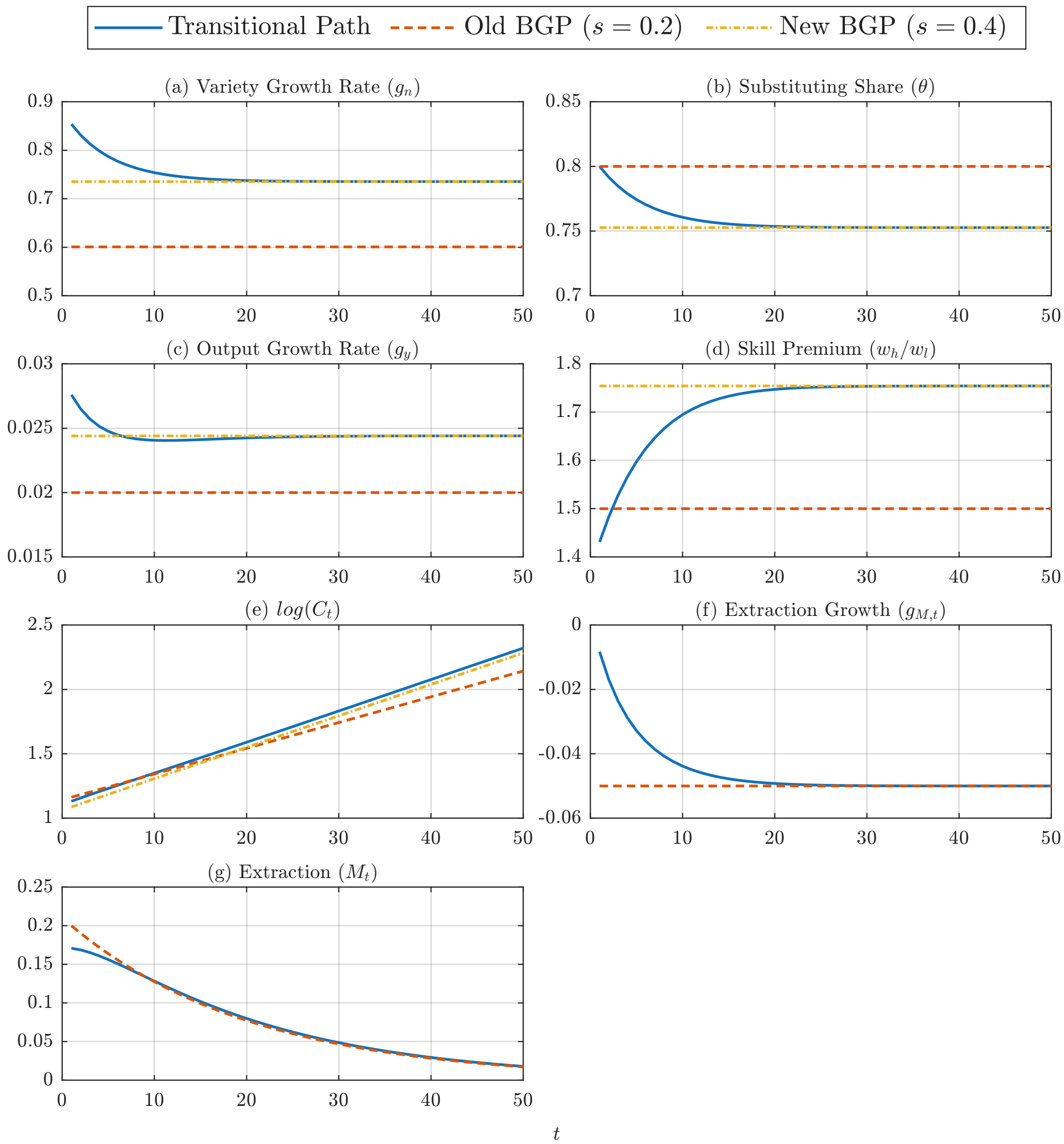

Figure 4: Dynamic Effects of the Variety R&D Subsidy Rate (s): Resource-Rich Economy ($S_0 = 4$)

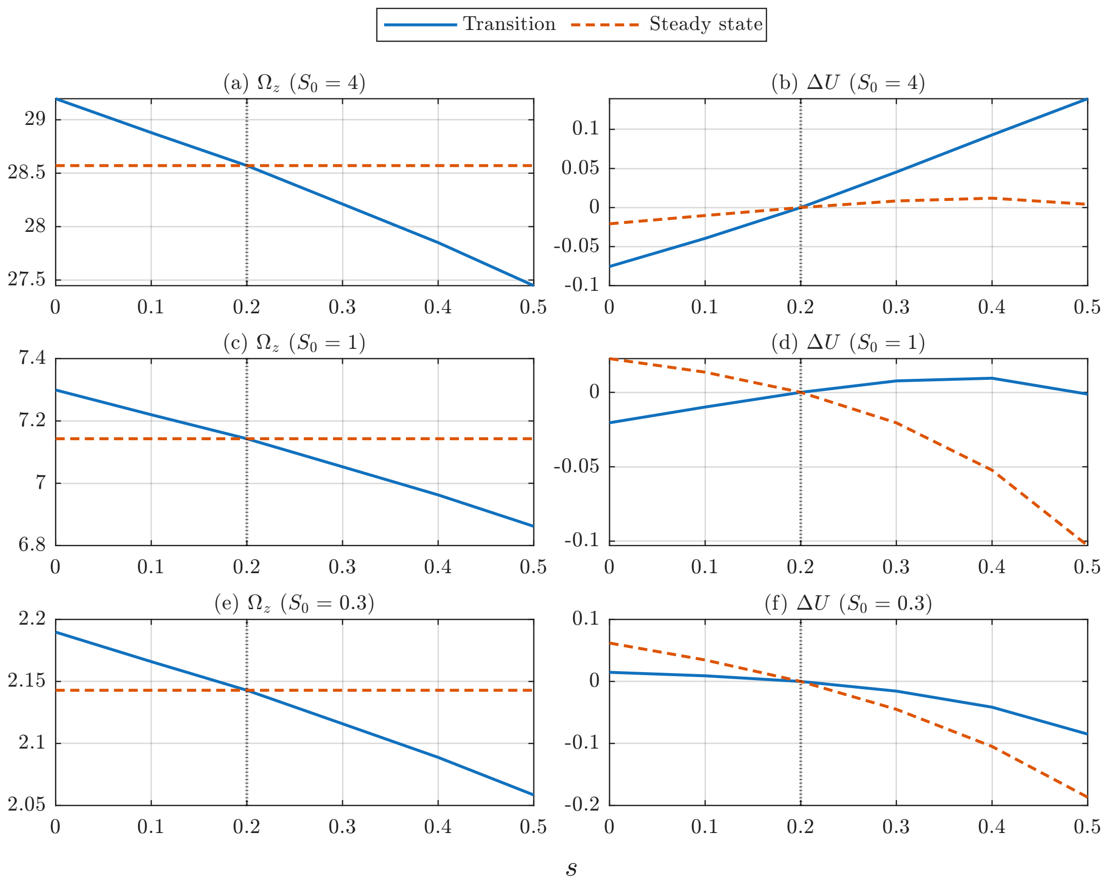

Figure 5: Effects of s on Transitional Ω_z and U for Different Values of S_0

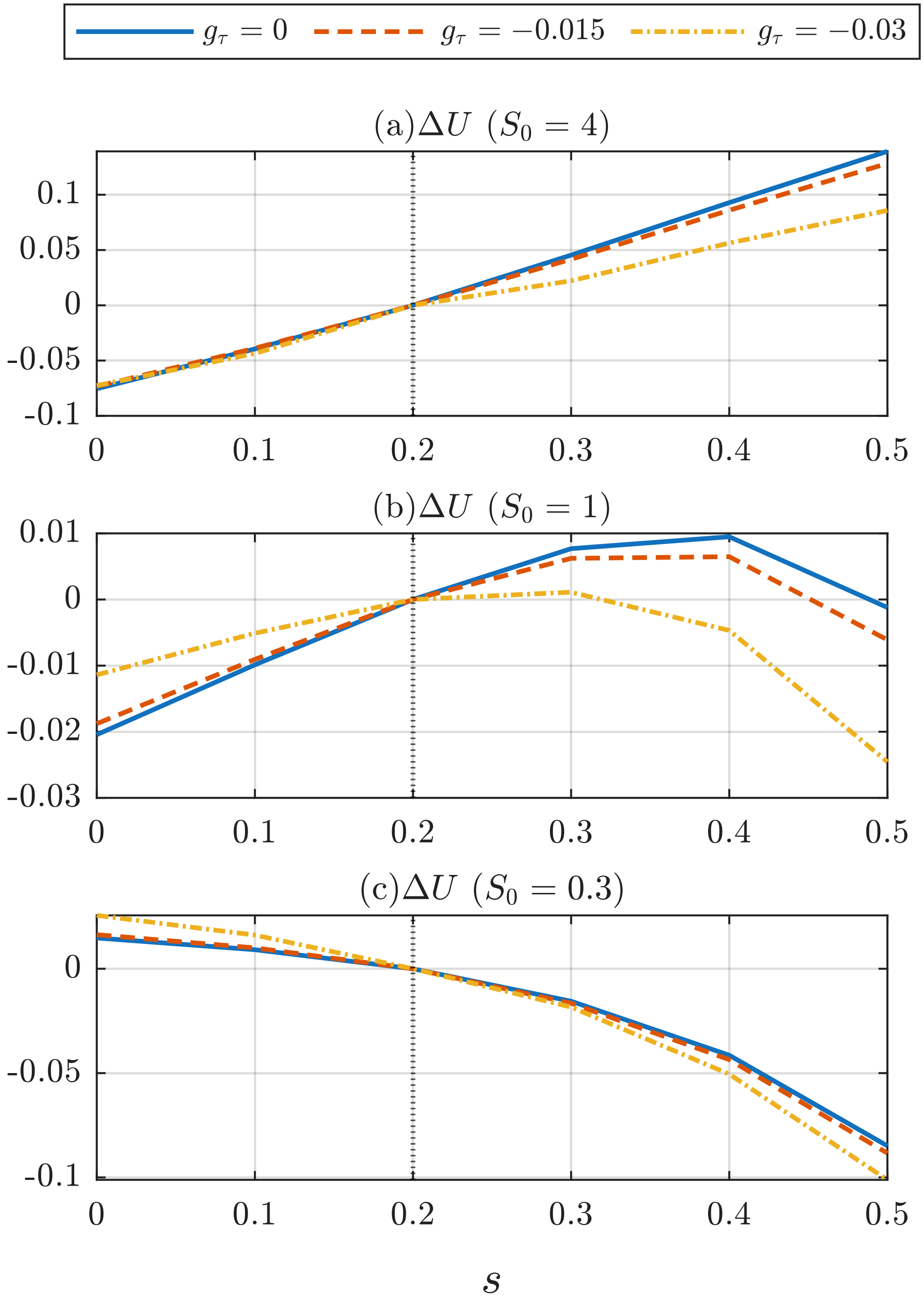

Figure 6: Effects of s on Transitional U for Different Values of g_τ

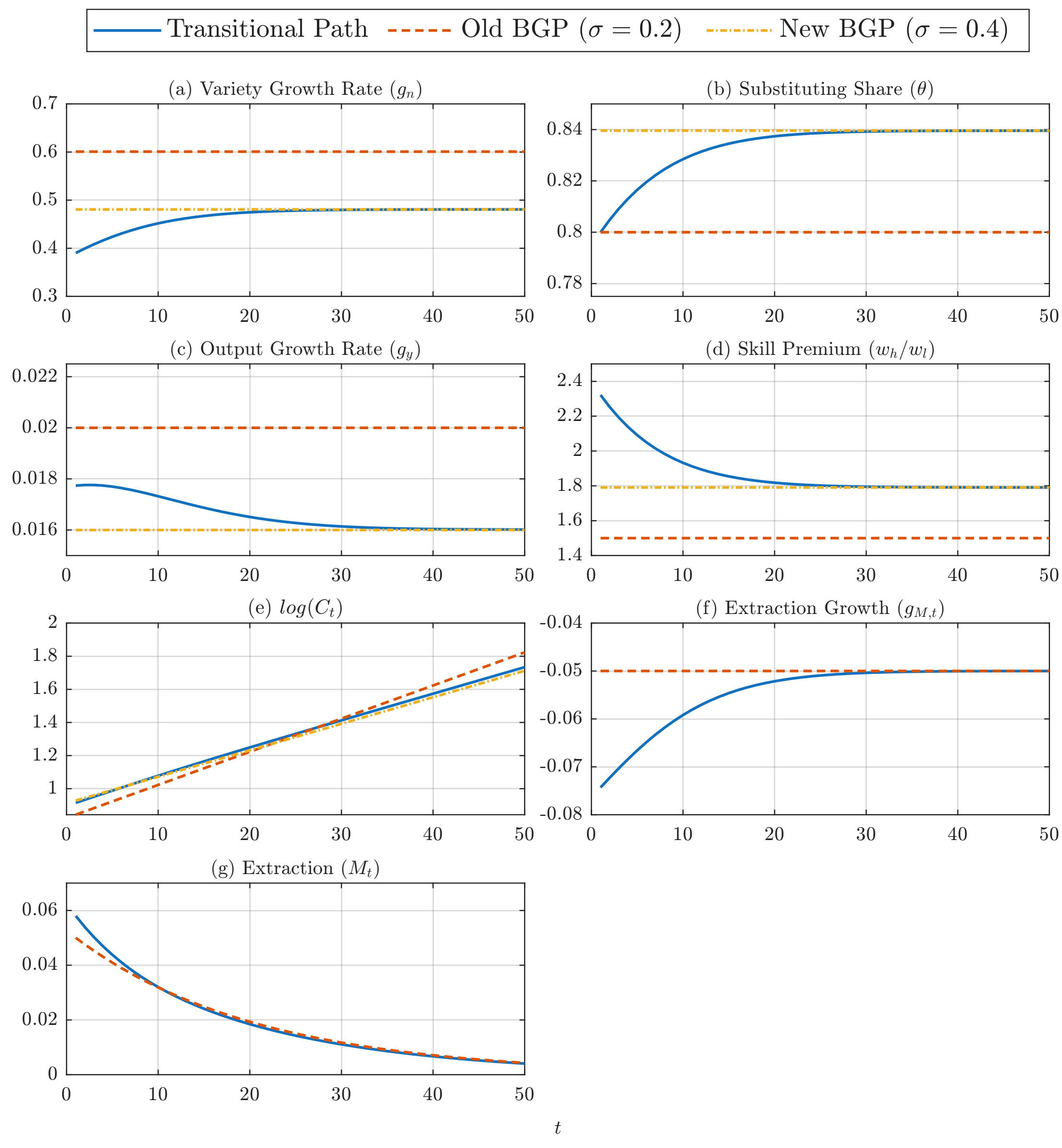

Figure 7: Dynamic Effects of the Resource-Substituting Technology Development Subsidy Rate (σ): Resource-Poor Economy ($S_0 = 1$)

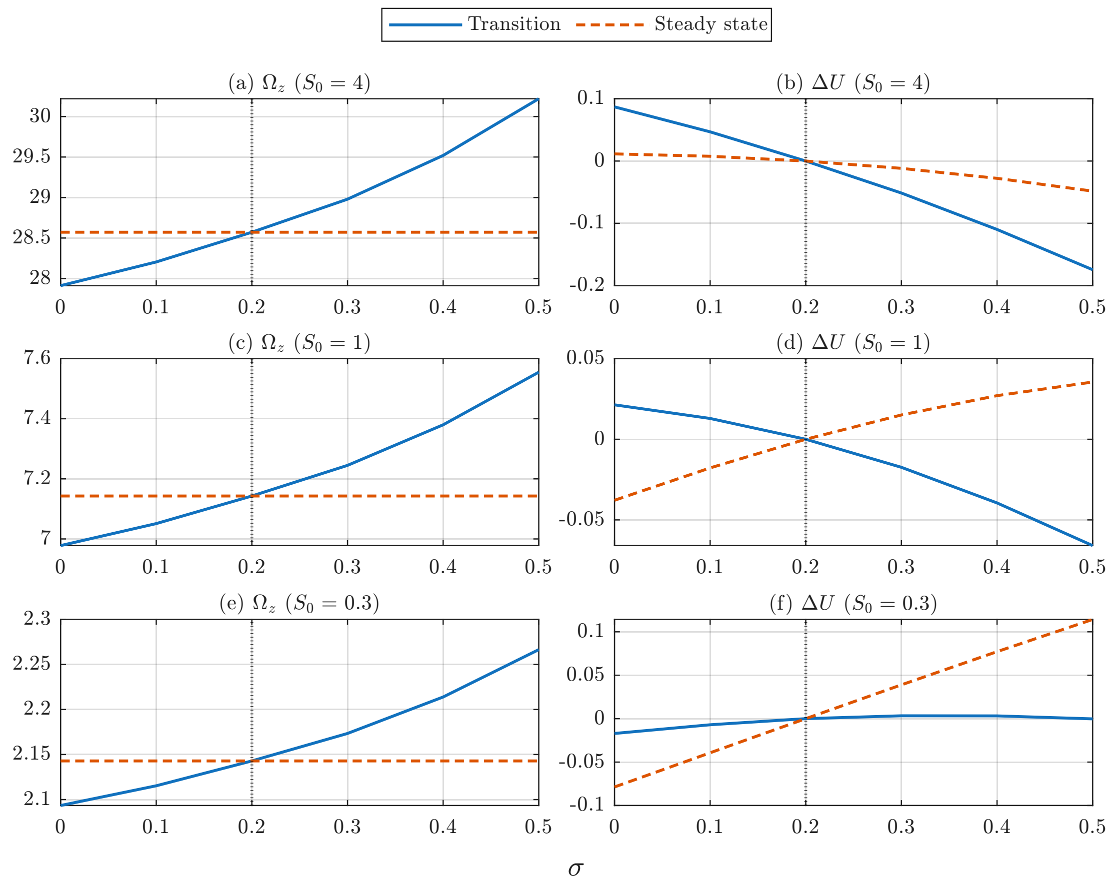

Figure 8: Effects of σ on Transitional Ω_z and U for Different Values of S_0

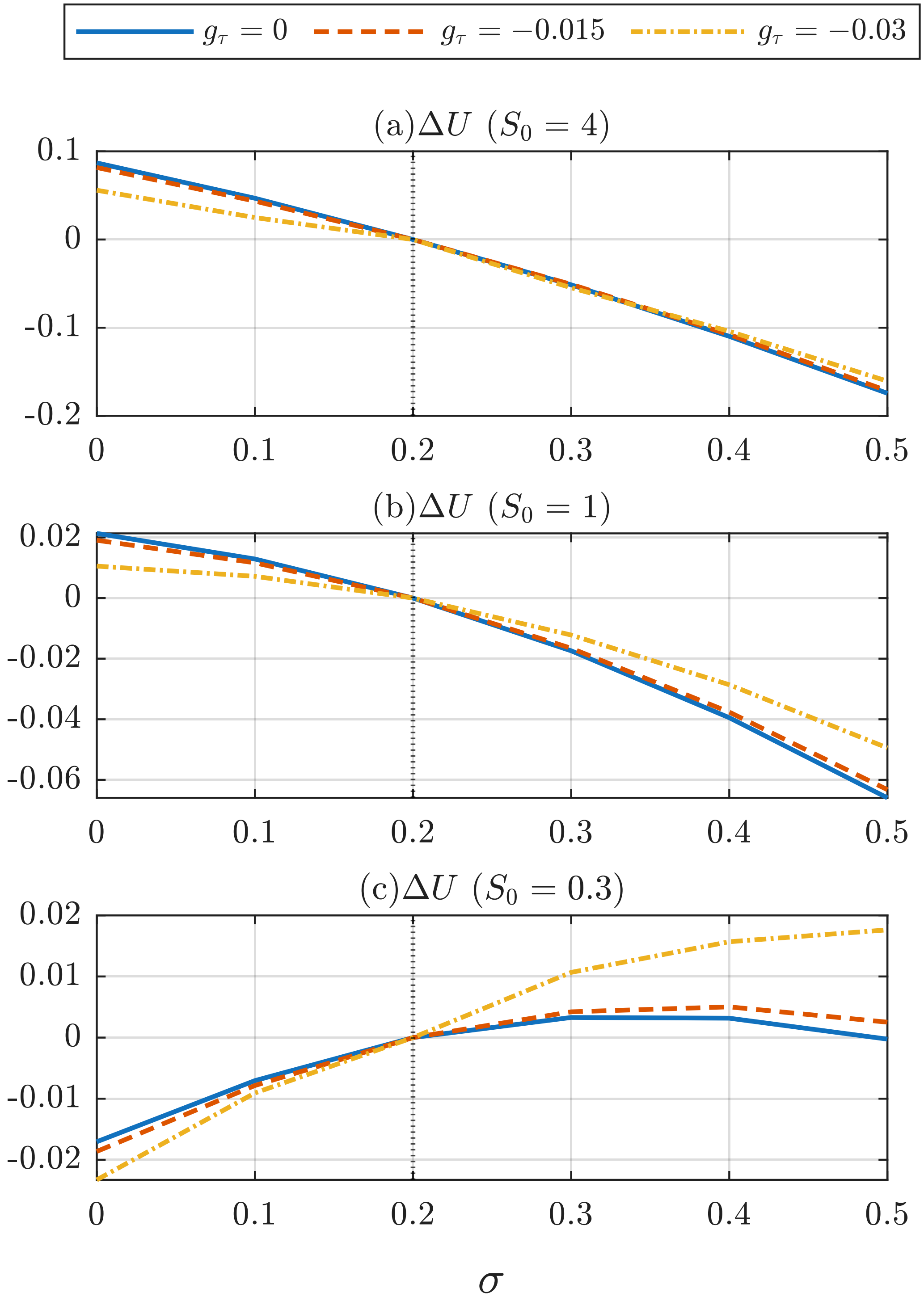

Figure 9: Effects of σ on Transitional U for Different Values of g_τ

References

[1] Acemoglu, Daron and Pascual Restrepo (2018a). "Modeling Automation," *AEA Papers and Proceedings*, 108, 48–53.

[2] Acemoglu, Daron and Pascual Restrepo (2018b). "The race between man and machine: Implications of technology for growth, factor shares and employment." *American Economic Review* 108(6), 1488–1542.

[3] Aghion, Philippe and Peter Howitt (2009). *The Economics of Growth*. Cambridge, MA: MIT Press.

[4] Britton, Erik, John Larsen, and Ian Small (2000). "Imperfect competition and the dynamics of markups." *Bank of England Working Paper* No. 110. Bank of England.

[5] Broda, Christian, Joshua Greenfield, and David E. Weinstein (2006). "From groundnuts to globalization: A structural estimate of trade and growth." *NBER Working Paper* No. 12512. National Bureau of Economic Research.

[6] Brunnschweiler, Christa N., Pietro F. Peretto, and Simone Valente (2021). "Wealth creation, wealth dilution and demography." *Journal of Monetary Economics* 117, 441–459.

[7] Chu, Angus C., Guido Cozzi, Yuichi Furukawa, and Chih-Hsing Liao (2023). "Should the government subsidize innovation or automation?" *Macroeconomic Dynamics* 27, 1059–1088.

[8] Dasgupta, Partha and Geoffrey Heal (1974). "The Optimal Depletion of Exhaustible Resources," *Review of Economic Studies*, 41, 3–28.

[9] Dasgupta, Partha and Joseph E. Stiglitz (1981). "Resource Depletion under Technological Uncertainty," *Econometrica*, 49(1), 85–104.

[10] Daubanes, Julien and André Grimaud (2010). "Taxation of a polluting non-renewable resource in the heterogeneous world." *Environmental and Resource Economics* 47(4), 567–588.

[11] Di Vita, Giuseppe (2001). "Technological Change, Growth and Waste Recycling," *Energy Economics*, 23(5), 549–567.

[12] Di Vita, Giuseppe (2004). "Renewable Resources and Waste Recycling," *Environmental Modeling & Assessment*, 9(3), 159–167.

[13] Galí, Jordi, Mark Gertler, and J. David López-Salido (2007). "Markups, gaps, and the welfare costs of business fluctuations." *Review of Economics and Statistics* 89(1), 44–59.

[14] Goh, Ai-Ting and Jacques Olivier (2002). "Optimal patent protection in a two-sector economy." *International Economic Review* 43(4), 1191–1214.

[15] Grimaud, André and Line Rougé (2005). "Polluting non-renewable resources, innovation and growth: Welfare and environmental policy." *Resource and Energy Economics* 27(2), 109–129.

[16] Grimaud, André and Line Rougé (2008). "Environment, directed technical change and economic policy." *Environmental and Resource Economics* 41(4), 439–463.

[17] Grimaud, André and Line Rougé (2014). "Carbon sequestration, economic policies and growth." *Resource and Energy Economics* 36(2), 307–331.

[18] Grossman, Gene M. and Elhanan Helpman (1991). *Innovation and Growth in the Global Economy.* Cambridge, MA: MIT Press.

[19] Hasna, Z., Jaumotte, F., Kim, J., Pienknagura, S., and Schwerhoff, G. (2023)."Green Innovation and Diffusion: Policies to Accelerate Them and Expected Impact on Macroeconomic and Firm-Level Performance," *IMF Staff Discussion Note*, No. 2023/008.

[20] Hémous, David and Morten Olsen (2022). "The rise of the machines: Automation, horizontal innovation and income inequality." *American Economic Journal: Macroeconomics* 14(1), 179–223.

[21] Intergovernmental Panel on Climate Change (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.). Geneva: IPCC.

[22] Jones, Charles I. and John C. Williams (1998). "Measuring the social return to R&D." *Quarterly Journal of Economics* 113(4), 1119–1135.

[23] Kamien, Morton I. and Nancy L. Schwartz (1978). "Optimal Exhaustible Resource Depletion with Endogenous Technical Change," *Review of Economic Studies*, 45(1), 179–196.

[24] Kümmel, Reiner, Jürgen Henn, and Dietmar Lindenberger (2002). "Capital, labor, energy and creativity: Modeling innovation diffusion." *Structural Change and Economic Dynamics* 13(4), 415–433.

[25] Lafforgue, Gilles and Luc Rougé (2019). "A Dynamic Model of Recycling with Endogenous Technological Breakthrough," *Resource and Energy Economics*, 57, 101–118.

[26] Nordhaus, W. D. (2021). *The Spirit of Green: The Economics of Collisions and Contagions in a Crowded World*, Princeton, NJ: Princeton University Press.

[27] Organisation for Economic Co-operation and Development (2024). "Environmentally related tax revenue (indicator)." Extracted from OECD.Stat (accessed February 27, 2024).

[28] Organisation for Economic Co-operation and Development (2025). *Education at a Glance 2025: OECD Indicators*. Paris: OECD Publishing.

[29] Organisation for Economic Co-operation and Development (2025). *OECD R&D Tax Incentives Database*.

[30] Pittel, Karen and Lucas Bretschger (2010). "The implications of heterogeneous resource intensities on technical change and growth." *Canadian Journal of Economics* 43(4), 1173–1197.

[31] Romer, Paul M. (1990). "Endogenous technological change." *Journal of Political Economy* 98(5), S71–S102.

[32] Sinn, Hans-Werner (2008). "Public policies against global warming: A supply-side approach." *International Tax and Public Finance* 15(4), 360–394.

[33] Stern, David I. (2000). "A multivariate cointegration analysis of the role of energy in the US macroeconomy." *Energy Economics* 22(2), 267–283.

[34] Stern, David I. (2011). "The role of energy in economic growth." *Annals of the New York Academy of Sciences* 1219, 26–51.

[35] Tabata, Ken (2026). "Taxing Polluting Resources: Growth, Welfare, and Consumption Inequality." *Canadian Journal of Economics*, forthcoming.

[36] Trimborn, Timo, Karl Koch and Thomas Steger (2008). "Multi-Dimensional Transitional Dynamics: A Simple Numerical Procedure," *Macroeconomic Dynamics*, 12(3), 301–319.

[37] Tsur, Yacov and Amos Zemel (2003). "Optimal Transition to Backstop Substitutes for Nonrenewable Resources," *Journal of Economic Dynamics and Control*, 27(4), 551–572.

[38] Tsur, Yacov and Amos Zemel (2005). "Scarcity, Growth and R&D," *Journal of Environmental Economics and Management*, 49(3), 484–499.

[39] Valente, Simone (2011). "Endogenous Growth, Backstop Technology Adoption, and Optimal Jumps," *Macroeconomic Dynamics*, 15(3), 293–325.

[40] van der Ploeg, Frederick and Cees Withagen (2012). "Is There Really a Green Paradox?" *Journal of Environmental Economics and Management*, 64(3), 342–363.

[41] van der Ploeg, Frederick and Cees Withagen (2015). "Global warming and the green paradox: A review of adverse effects of climate policies." *Review of Environmental Economics and Policy* 9(2), 285–303.

[42] van der Meijden, Gerard and Sjak Smulders (2017). "Carbon lock-in: The role of expectations." *International Economic Review* 58(4), 1371–1415.

[43] van der Meijden, Gerard and Sjak Smulders (2018). "Technological Change During the Energy Transition," *Macroeconomic Dynamics*, 22(4), 805–836.

[44] Zeira, Joseph (1998). "Workers, machines, and economic growth." *Quarterly Journal of Economics* 113(4), 1091–1117.