Redistributive Innovation Policy, Inequality and Growth

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Abstract

We examine the efficiency and distributional effects of regressive and progressive public R&D policies that target high-tech and low-tech sectors using a heterogenous-agent growth model with in-house R&D and incomplete capital markets. We find that such policies have important implications for efficiency, inequality and social mobility. A regressive public R&D investment financed by income tax could boost growth and welfare via a positive effect on individual savings and effort. However, it could also lower growth and welfare via its effect on the efficiency–inequality trade off. Thus, the relationship between public R&D spending and welfare is hump shaped admitting an optimal degree of regressivity in public R&D spending. Using our baseline model and the US state level GDP data, we back out the degree of regressivity of public R&D investment in US states. A case for optimal progressive public R&D investment can be made with a properly designed R&D policy that combines consumption tax and investment subsidy.

Key words:
Public R&D investment, inequality dynamics, social mobility, growth, welfare
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1. Introduction

The role of public and private R&D (research and development) investment in economic growth is a widely debated topic.[1] However, the distributional effect of public R&D investment has received little attention. In the extant literature, the focus is more on public education (e.g., Glomm and Ravikumar, 1992, 2003, Benabou, 2002) and infrastructure and taxes (e.g., Garcia and Turnovsky, 2007, Getachew, 2010, Chatterjee and Turnovsky, 2012, Getachew and Turnovsky, 2015). R&D investment could have uneven impacts on the economy and through this channel impacts rich and poor differently. In general, most public R&D investment in developed countries are concentrated on high-tech industries such as information technology, biotechnology, communication, and environment industries. In the United States, for instance, public investment in equipment and software has increased from 20% in 1980 to 50% in 2001 which contributed to rising inequality in the US in recent decades (Cozzi and Impullitti, 2010).[2] In contrast, in most of the developing world, a significant amount of public R&D investment are made in agriculture, a low-tech sector dominated by small scale farmers. Beintema et al. (2012) report an accelerated public investment in agricultural R&D in developing countries during the period 2000 and 2008. Using provincial data in China spanning more than four decades, Zhang and Fan (2004)

[1] Particularly, in early 90s, there was an influx of R&D based growth theories, following the seminal works by Romer (1990), Grossman and Helpman (1991) and Aghion and Howitt (1992) that emphasize the role of R&D to economic growth, through influencing technological progress. R&D policies are also widely debated as to whether public R&D investment complements private R&D investment or crowds it out (e.g., David et al., 2000).

[2] Kim et al. (2013) argue that R&D investment in South Korea is concentrated more on high-tech sectors.

argue that government spending on agricultural R&D contributed to a reduction in regional inequality.

Our own calculations suggest a contrasting relationship between inequality and public R&D spending, consistent with previous studies. Figures 1 and 2 show relationships between the Gini index and share of the public R&D spending in the U.S. and Sub-Saharan Africa (SSA), respectively. In both regions, public R&D spending has sharply increased during the last two decades, but the inequality experience is opposite.[3] While there is a positive correlation between Gini and R&D investment across US states, for SSA countries the correlation is negative.[4]

[3] The average annual agricultural R&D spending growth in SSA countries, for instance, increased from 0.3% during 1981-1990 to 2.8% during 2000-2008 except for a small dip of .01% during 1990-2000, which is indicative of the bulk of recent R&D innovations in SSA being progressive in nature (Beintema et al., 2012).

[4] The R&D intensity is measured by the ratio of total R&D spending (including private and public GDP) to state GDP. All the Gini data came from US Census Bureau. The R&D intensity data came from the Science, technology, Innovation and Entrepreneurship (SSTI) database of the US. The correlation coefficient between R&D Intensity and State Gini index is 0.18. For SSA countries the Gini and public R&D spending data came from World Development Indicators (2015). Due to sparse nature of the data, we take the average of Gini index from 2000 onward whatever data are available. Same is done for the public R&D spending ratio.

Figure 1: Inequality and R&D Spending in US States

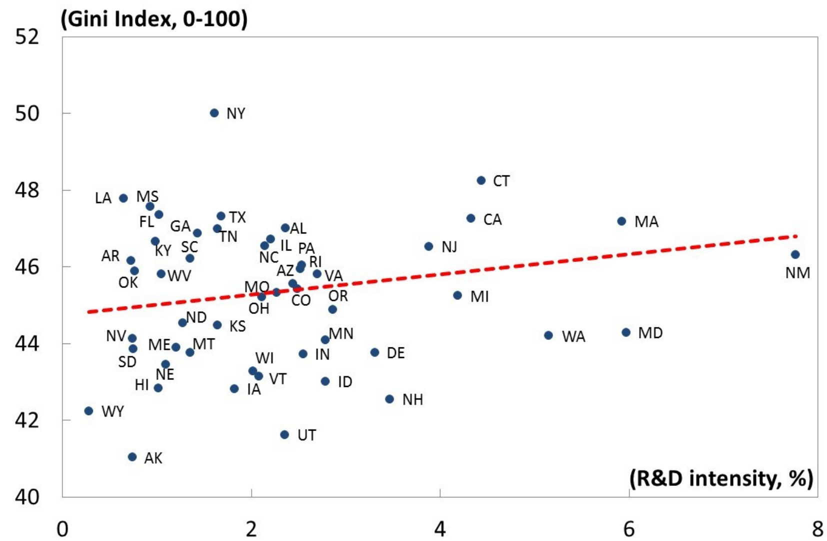
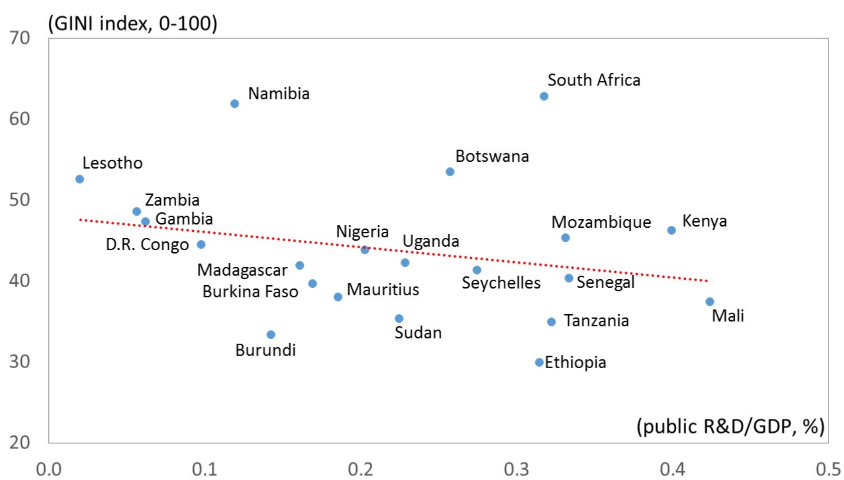


Figure 2: Inequality and PublicR &D Spending in SSA



The aim of this paper is to examine the effects of progressive and regressive redistributive innovation policies on efficiency, inequality and social mobility. We develop a heterogenous-agent growth model with in-house R&D where both inequality and growth are endogenously determined. In the model, agents are heterogenous in their initial endowments of knowledge and their ability to generate knowledge. The source of endogenous growth is in-house R&D investment using private and public resources. Endogenous inequality is generated due to missing credit and insurance markets, as in Loury (1981) and Benabou (2000, 2002, 2005). The dynamics of aggregate variables and inequality are jointly determined in the model that admits a closed-form analytical solution.

We do three related exercises using this framework. First, we analyze the effects of progressive (benefiting poor) and regressive public R&D investment policies (benfiting rich) on inequality, social mobility, growth and welfare, which is the main objective of this paper. Regressive R&D investment policy aggravates inequality and slows down social mobility. On the other hand, regressive innovation policies have the benefit of promoting efficiency due to positive incentives on agents' savings and work effort decisions. There is a potential trade-off between growth and inequality in our model due to incomplete capital markets. This makes the relationship between R&D investment, growth as well as welfare nonlinear and hump shaped admitting an optimal degree of regressivity. Second, going further, we use our model and the state level GDP data for the US, we back out the degree of regressivity in each US state. We find that inequality is higher in US states where R&D spending is more regressive. This exercise lends empirical support to our model which predicts that a regressive innovation policy could exacerbate inequality. Finally, we do a policy exercise to find whether there is any case for progressive R&D policy in our present setting. We show that a case for optimal progressive R&D policy can be made if the R&D investment subsidy is financed by consumption taxation. Such a consumption tax basically absorbs the brunt of distortion caused by progressive R&D policy, making savings and labour supply free from distortion. As a result, the policy maker can push the progressive R&D policy to its maximum limit without hurting private incentive for savings and work efforts. This produces a second best tax-subsidy scenario of neutral R&D innovation. To the best of our knowledge, this case for such an optimal progressive R&D policy is novel in the literature.

Our work connects to a wider literature on inequality, social mobility and growth. First, it relates to the literature that analyzes growth–inequality trade off under imperfect credit markets although this literature abstracts from productive public spending feature of our model.[5] For instance, the work of Benabou (2002) focuses primarily on the distributional and growth impact of progressive taxation while our focus is on the redistributive effects of productive public goods. Second, the paper is in line with the literature on public education, infrastructure and inequality[6] despite the scant attention they pay to public R&D investment. Third, our work complements a growing literature on innovation and inequality (Chu, 2010, Cozzi and Impullitti, 2010, and Aghion et al., 2015) with the following important differ-

[5] See for example Loury, (1981), Galor and Zeira (1993), Aghion and Bolton (1997), Aghion, et al. (1999) Benabou (2000, 2002, 2005) and Basu and Getachew (2015).

[6] Public education is at the center of the work by Glomm and Ravikumar (1992, 2003), Saint-Paul and Verdier (1993) and Eckstein and Zilcha (1994), among many others. In contrast, recent work by Garcia-Penalosa and Turnovsky (2007), Getachew (2010, 2012), Chatterjee and Turnovsky (2012), and Getachew and Turnovsky (2015) focus on the effects of infrastructure on inequality.

ences. We focus on contrasting the effects of regressive and progressive innovation, predicting US regional inequality and designing an optimal regressive and progressive R&D policy while the focus of the above studies is more on the effects of innovation or innovation policy on inequality and social mobility.[7] Finally, our study accords well with a branch of literature that attributes the recent rise in inequality in many advanced economies to skill biased technical change (Acemoglu, 2002 and Aghion, 2002). This literature, however, focuses on private R&D investment or technical progress and abstracts from the optimal public R&D policy and the R&D effects on US regional inequality that we are interested in.

The paper is organized as follows: The next section develops the model. Section 3 characterizes individual and aggregate (inequality) dynamics. Section 4 discusses the effects of different R&D policies on steady-state growth and inequality while Section 5 focuses on optimality of alternative R&D policies. Section 6 presents estimates of the degree of regressivity in the US states using state level GDP data and compares this with state-level Gini coefficient. Section 7 addresses the issue of optimal progressive R&D policy. Section 8 concludes.

2. The Model

We assume that the economy is populated with a continuum of heterogenous agents, $i \in (0,1)$. There is no population growth in the economy. The first generation of the ith agent is endowed with h_{i0} levels of knowledge. Initial distribution is given

[7] Chu (2010) argues that strengthening patent policy increases income inequality by raising the return on assets. Whereas, Aghion et al. (2015) focus on the relationship between innovation, top income inequality and social mobility for the U.S..

and assumed to take log-normal, $\ln h_{i0} \sim N(\mu_0, \sigma_0^2)$, which evolves endogenously at equilibrium. Agents also differ in their respective productivity and creativity to generate income and knowledge, respectively, where both are assumed to be i.i.d. and log-normally distributed. Combined with labour, knowledge is used to produce intermediate goods, which are, in turn, used for production of the final goods.

There are three sectors in the economy, namely the final goods, the intermediate goods and the knowledge production sectors. Using a CES production function, a competitive firm transforms intermediate inputs into a final good. These differentiated intermediate inputs are produced by monopolistically competitive firms.Each firm in this sector invests in an in-house R&D, in the spirit of Smulders and Van de Klundert (1995), to expand a specialized know-how that is required to produce a specialized input. The production of knowledge requires both the use of public and private resources, and a backlog of knowledge stock. The government levies a fixed flat rate tax on the income of individual agents to finance the 'public good'. This public good is provided *disproportionately* among rich and poor agents to supplement private R&D investment.

2.1. Final goods

In the spirit of Benabou (1996), the final goods and services are produced using a continuum of differentiated intermediate inputs (x_{it}) by the representative firm in the economy:

$$y_t = a_1 \left(\int_0^1 \phi_{it} x_{it}^{(\varepsilon-1)/\varepsilon} di \right)^{\varepsilon/(\varepsilon-1)} ; \varepsilon > 1 \tag{1}$$

where x_{it} is the intermediate input supplied by the ith intermediate goods firm and a_1 is a deterministic TFP parameter; ϕ_{it} represents idiosyncratic productivity shocks, which are i.i.d. with mean one and a constant non-zero variance, attached to each intermediate input:

$$\ln \phi_{it} \sim N\left(-\varkappa^2/2, \varkappa^2\right)$$

$\varepsilon > 1$ is the elasticity of substitution between the intermediate inputs, which determines the firms' monopoly power, in the spirit of Dixit and Stiglitz (1977).

Profit maximization by the perfectly competitive firm, given a unit price of the final goods, leads to the downward slopping input demand function:

$$x_{it} = \phi_{it}^{\varepsilon} a_1^{\varepsilon-1} y_t \left(\frac{1}{p_{it}}\right)^{\varepsilon} \tag{2}$$

where p_{it} denotes the price of the ith intermediate good and $-\varepsilon$ is the price elasticity of demand.

2.2. Intermediate goods

The differentiated intermediate goods firms are characterized with certain features. First is the presence of specialization. Knowledge is firm-specific, and hence the production of intermediate goods. Thus, each intermediate goods firm has some monopoly power over its price. Consequently, the rate of returns and earnings are different among firms in this sector. Second, a firm in this sector engages in an in-house R&D investment to expand its specialized knowledge stock. The R&D investment is the only vehicle of technical progress.

As in Aghion et al. (2015), the ith firm in the intermediate goods sector needs

$1/h_{it}$ units of labour to produce one unit of its variety:

$$x_{it} = h_{it} l_{it} \tag{3}$$

where h_{it} represents the stock of the firm specific knowledge, generated through in-house R&D activity, which is specified below; and, l_{it} is the raw labour input. Each period, the firm's profit consists of revenue from the sale of the intermediate good, x_{it}, net of the total labor cost $(l_{it} w_{it})$ where w_{it} is the wage rate per unit of labor. Thus, the firm has the following static optimization problem,

$$\max_{\{l_{it}, p_{it}\}} \pi_{it} = p_{it}\left(x_{it}, .\right) x_{it} - w_{it} l_{it}$$

subject to the demand function (2). The first order condition leads to the following pricing:

$$p_{it} = \left(w_{it}/h_{it}\right) \varepsilon / \left(\varepsilon - 1\right) \tag{4}$$

While w_{it}/h_{it} is the marginal cost of producing a unit of the intermediate input, the elasticity of substitution, ε, determines the mark-up over this cost.

The ith agent income which is the sum of wages and profit income is given by:

$$y_{it} = p_{it} x_{it} \tag{5}$$

Plugging (2), (3) and (4) into (5), one obtains:

$$y_{it} = a\phi_{it} \left(l_{it}h_{it}\right)^{\alpha} y_t^{1-\alpha} \tag{6}$$

where $a \equiv a_1^{(1-\varepsilon)/\varepsilon}$.[8]

Eq. (6) is the reduced form individual production function that matches individual income to output production, characterized by constant returns to scale at individual (h_{it}) and aggregate accumulative factors (h_t) in total.[9] However, there is diminishing returns to individual factor. This shows that the model is basically in the spirit of the Arrow (1962) and Romer (1986) learning-by-doing endogenous growth models.

2.3. In-house R&D

Each intermediate goods firm invests in an in-house R&D to produce the know-how using the following knowledge production function:

$$h_{it+1} = \zeta_{it+1} h_{it}^{\theta} s_{it}^{\nu} g_{it}^{\lambda} \tag{7}$$

Government intervenes in the R&D process by investing in public R&D input (g_{it}) that uses to complement the private sector, but with a redistributive intent. According to (7), knowledge is a product of both public and private investment (g_{it} and s_{it}, respectively), past knowledge stock of the firm (h_{it}) and idiosyncratic shocks (ζ_{it+1}). $\{\theta, \lambda, \nu\} \in (0, 1)$ denote knowledge elasticities. ζ_{it+1} is i.i.d. and follows a log-normal

[8] To derive (6), equate (2) and (3) to solve $p_{it} = \phi_{it} a_1^{(1-\varepsilon)/\varepsilon} y_t^{(1/\varepsilon)} (h_{it} l_{it})^{-(1/\varepsilon)}$ which upon plugging into (5) and rearranging terms yields (6).

[9] As we see later, y_t is a linear function of h_t and $l_{it} = l$, which is constant.

distribution with mean one and a constant variance,

$$\ln \zeta_{it+1} \sim N\left(-\varrho^2/2, \varrho^2\right)$$

The production function (7) exhibits constant-returns to scale ($\theta + \nu + \lambda = 1$), which makes the growth process endogenous as in any standard growth model.

2.4. Government budget

Public R&D investment is financed using a proportional income tax (τ), which is levied in the final goods. The government balances the budget as in the growth and public investment literature (e.g., Barro, 1990):

$$g_t = \tau \int_0^1 y_{it} di = \tau y_t \tag{8}$$

where g_t denotes the total public investment in R&D and τ is the public expenditure GDP ratio. Thus, a fraction of aggregate income is used to finance the public good.

The *key* feature of this paper lies in the relationship between the production of knowledge and public expenditure. We abstract from a blanket public investment provision in R&D. Rather the government expenditure in R&D has a redistributive component. Public R&D investment does not necessarily benefit individual firms proportionally. Small firms may benefit disproportionately from low-tech technologies as large firms do from high-tech technologies. For instance, an innovation of a pedal-powered tractor is more beneficial to small-scale farmers, as a high-powered tractors for large commercial farms. Formally, this can be expressed as

$$g_{it} = (h_{it}/h_t)^{\omega}\, g_t \tag{9}$$

The key redistributive R&D policy parameter is ω. Its magnitude and sign determine the weight and nature of redistribution, respectively. If $\omega = 0$, for instance, $g_{it} = g_t$ is a pure public good where all firms equiproportionately benefit from public R&D. We call such a R&D policy neutral because it is not biased towards the rich or poor. A positive ω implies merit-based public expenditure. R&D firms with a relatively high level of initial knowledge stock compared to the average knowledge stock (meaning a higher h_{it}/h_t) benefit more than proportional from public R&D spending (g_t). A negative ω, on the other hand, makes small firms with a relatively lower level of initial knowledge stock (a lower h_{it}/h_t) benefit more from public spending on R&D. Hereafter, we refer to negative ω and positive ω as *progressive* and *regressive* public expenditure, respectively, in line to the literature in progressive/regressive taxation.[10]

Combining (7) and (9) one obtains:

$$h_{it+1} = a_2 \zeta_{it+1} h_{it}^{\theta+\omega\lambda} s_{it}^{\nu} \left(g_t/h_t^{\omega}\right)^{\lambda} \tag{10}$$

The parameters θ and λ are *ex ante* knowledge elasticities whereas $\theta + \omega\lambda$ and $\lambda - \omega\lambda$ capture *ex post* intergenerational linkages associated with firm level knowl-

[10] In Benabou (2000, 2002), for instance, after-tax income is given by $\widehat{y}_{it} = (y_{it}/\widetilde{y}_t)^{\tau}\, \widetilde{y}_t$ where y_{it} and $\widetilde{y}_t$ represent before-tax and threshold incomes, respectively; τ, which has basically a similar role as ω has in our model, represents the marginal tax rate whose sign determines the progressivity/regressivity of the tax schedule. We differ from this literature, however, as we focus on the expenditure side.

edge production that account for individual and aggregate factors in the economy, respectively.[11] The term $\omega\lambda$ captures the redistributive nature of the public variable and its implication for individual knowledge accumulation. Redistribution thus impacts the economy via the effect on private and public knowledge elasticities. We see later individual optimal decision is crucially dependent on $\theta + \omega\lambda$, which is also the main determinant of the evolution of inequality, which, in turn, determines other macroeconomic dynamics.

2.5. Household

There is a continuum of households indexed between $(0, 1)$. Households own the firms and also work in the R&D sector.[12] Similar to Benabou (2002, 2005), the credit and insurance markets are missing. We also assume members of the households are endowed with units of labour that they supply elastically. Agents maximize their utility in accordance of the following function:

$$U_{it} \equiv \max_{\{c_{it}, h_{it+1}, l_{it}\}_0^\infty} \mathrm{E}_t \sum_{t=0}^{\infty} \rho^t \left(\ln c_{it} - l_{it}^{\eta} \right) \tag{11}$$

where $\eta > 1$; E_t is an individual's expectation given information at date t. The budget constraint is given by:

$$c_{it} + s_{it} = (1 - \tau)\, y_{it} \tag{12}$$

[11] As we shall soon see g_t is a linear function of h_t.

[12] Other models that use similar type of individual entrepreneurship include Benabou (2000, 2002, 2005) and Angeletos and Calvet (2005, 2006).

where τ represents a flat rate income tax on both wage and profit income.

Applying standard methods, individual household decision rules can be derived as follows:

$$s_{it} = b\,(1-\tau)\,y_{it} \tag{13a}$$

$$l_{it} = l = (\alpha/\,(\eta\,(1-b)))^{1/\eta} \tag{13b}$$

$$c_{it} = (1-\tau)\,(1-b)\,y_{it} \tag{13c}$$

where

$$b \equiv \rho\alpha\nu/\,(1-\rho\,(\theta+\omega\lambda)) \tag{14}$$

Eqs. (13) are standard forms from the view point of household optimization. Households supply a constant unit of labour while saving rate is independent of rate of returns, as a consequence of log utility function. Both saving rate and effort increase with the discount factor (ρ), elasticity of substitution (ε), intergenerational spillover (θ), and the elasticity of private investment (ν). But, the effect of ω and λ on saving rate and labor supply depend on the sign of ω. Both increase if the R&D program is regressive ($\omega > 0$) while they decrease if it is progressive ($\omega < 0$), the classic efficiency–equity trade off. We thus have the following proposition:

Proposition 1. *Saving rate and labour supply increase (decrease) with regressive (progressive) public R&D investment.*

Proof. See eqs. (13a) and (13b). ■

2.5.1. Aggregate consumption, investment and income:

Aggregate consumption and savings are given by

$$c_t = (1-\tau)(1-b)\, y_t \tag{15}$$

$$s_t = (1-\tau)\, b y_t \tag{16}$$

Aggregate income is derived from aggregating (6), after substituting (13b):

$$y_t = l a^{1/\alpha} h_t \exp(d_t) \tag{17}$$

where d_t is a composite parameter, which captures the relationship between aggregate income and inequality:

$$d_t \equiv 0.5\,(\alpha - 1)\,\sigma_t^2$$

In this case, the government budget constraint is given by, from (8) and (17):

$$g_t = \tau l a^{1/\alpha} h_t \exp(d_t) \tag{18}$$

where l is given by (13b). Given that individuals' income is determined by their optimal labor supply, aggregate labor is an important component of aggregate income and hence aggregate public R&D expenditure. In addition, considering $d_t < 0$, the existence of diminishing returns in individual income combined with missing credit markets implies that aggregate income, and hence public R&D decrease in inequality.

3. Dynamics

3.0.2. Optimal knowledge dynamics and intergenerational mobility

The dynamics of optimal knowledge stock associated to the ith firm is derived from (6), (10) (13a), (13b), (17) and (18):

$$h_{it+1} = a_3 \psi \chi \zeta_{it+1} \phi_{it}^{\nu} h_{it}^{\beta} h_t^{\kappa} \exp\left(\left(\lambda + (1-\alpha)\nu\right) d_t\right) \tag{19}$$

where $a_3 \equiv (\alpha/\eta)^{(\nu+\lambda)/\eta} a^{(\nu+\lambda)/\alpha}$ and

$$\psi \equiv b^{\nu} (1-b)^{-(\nu+\lambda)/\eta} \tag{20a}$$

$$\chi \equiv \tau^{\lambda} (1-\tau)^{\nu}$$

$$\beta \equiv \theta + \omega\lambda + \alpha\nu \tag{20b}$$

$$\kappa \equiv \lambda + (1-\alpha)\nu - \omega\lambda$$

Eq. (19) captures the optimal dynamics of knowledge at a firm level. τ and ω are policy parameters while the rest are structural parameters. The government adjusts the size of investment through its choice of τ whereas the sign of ω determines the redistributive nature of the public fund. Such policy variables impact the TFP of individual knowledge production function via their effects on individual savings, effort and public R&D investment. These are in particular reflected in ψ and χ. As captured in χ, there is a positive effect from income tax through its financing of public R&D expenditure; but, a negative effect in its distortionary effects on individual savings. The resultant effect is determined by the weight of the respective elasticities. From the expression of ψ, redistribution (ω) affects individual knowledge production through its effects on individual saving rate and effort. Redistributions also impact the elasticities of past knowledge (β, κ) with an important implication to inequality dynamics.

The dynamics of optimal individual knowledge also depends on the current individual and aggregate knowledge variables, idiosyncratic risks both in the final goods (ϕ_{it}) and R&D sectors (ζ_{it+1}) and current inequality. Risks in the final goods sectors affect individual savings and investment indirectly via individual income whereas those in the knowledge sector have a direct impact. The exponential term in (19) captures the relationship between inequality and individual knowledge dynamics. $d_t < 0$ reflects the negative effects of inequality on knowledge production at firm level. Through its impacts on aggregate and subsequent individual savings and investment, inequality negatively impacts individual knowledge accumulation.

3.1. Intergenerational mobility

The model has a direct implication for intergenerational mobility, as in Basu and Getachew (2015). The intergenerational elasticity (IGE) of knowledge (β) is derived from (19), first by taking logs from both sides of the equation, and then computing the partial derivative of the next-period knowledge with respect to the current knowledge:

$$\beta \equiv \partial \ln h_{it+1} / \partial \ln h_{it} = \theta + \omega\lambda + \nu\alpha \tag{21}$$

$1 - \beta$ is a measure of intergenerational mobility.

We are measuring mobility in terms of knowledge while in majority of the literature it is measured in terms of income (see, for instance, Solon, 1992 and Mazumder, 2005, among others). Given that knowledge is the only input in the production function, it is straightforward to verify from (13a) that β also governs the intergenerational persistence of income.

According to (21), intergenerational mobility is independent of the idiosyncratic shocks, but it depends crucially on the structure of goods and knowledge production and knowledge accumulation technologies at the individual household level.

Proposition 2. *Intergenerational mobility increases in progressive public R&D expenditure ($\omega < 0$), and conversely.*

Proof. See (21). ■

3.2. Inequality dynamics

The dynamics of inequality is also derived from (19), by taking the log and variance,

$$\sigma_{t+1}^2 = \nu^2 \varkappa^2 + \varrho^2 + \beta^2 \sigma_t^2 \tag{22}$$

Given $\beta \in (0,1)$, (22) is a stable dynamics that converges to a steady state inequality. The variance of the idiosyncratic shocks ($\varkappa^2$ and ϱ^2) will determine the long-run property of the model. Volatility in the final goods sector affects inequality via its effect on individual savings while volatility in the R&D sector directly impacts inequality dynamics. The root of the dynamics of inequality is determined by β, which, in turn, is a function of policy and structural parameters, ε, λ, ω, ν and

θ. Higher intergenerational linkage (higher θ) results in higher transitional inequality. Better private investment technology (higher ν) implies slower convergence in inequality. Private R&D investment elasticity (ν) also impacts inequality through individual response to luck, with a strong implication to long-run inequality.

The effect of the public variables on the dynamics of inequality rather depends on its redistributive feature (the sign of ω). If $\omega < 0$, higher elasticity of public R&D investment (higher λ) leads to faster convergence of inequality, and conversely. If $\omega = 0$, i.e. public investment in R&D is proportionally provided, however, the elasticity λ has a neutral effect in inequality. We thus have the following proposition:

Proposition 3. *A regressive (progressive) R&D investment aggravates (mitigates) transitory inequality. In other words, if $\omega > 0$ ($\omega < 0$), given σ_t^2, σ_{t+1}^2 increases (decreases) in ω, and conversely.*

Proof. From (22), if $\omega < 0$, for given σ_t^2 then σ_{t+1}^2 decreases in $|\omega|$, and conversely. ■

Note also that slower mobility (higher β) also implies slow convergence of the inequality dynamics. That is, the greater β is, the more persistent inequality becomes. However, since the coefficient in the inequality dynamics (β^2) is smaller than the mobility coefficient (β), intergenerational immobility is much more persistent than inequality.

3.3. Income and consumption inequality

Income inequalty (σ_{yt}^2) is a simple transformation of knowedge inequality based on the reduced form production function (6). Since equilibrium labour supply, l_{it} is constant,

$$\sigma_{yt}^2 = \varkappa^2 + \alpha^2 \sigma_t^2 \tag{23}$$

Since private consumption (c_{it}) is proportional to private income, the consumption inequality (σ_{ct}^2) is equal to income inequality (σ_{yt}^2) in this setting.

4. Steady state

Note that given $\beta \in (0,1)$, which is the sufficient condition for the stability of the distributional dynamics, (22) converges to a unique inequality equilibrium. But, with constant-returns to scale in knowledge production, inequality is the only source of dynamics in the economy. As inequality converges to its equilibrium level, growth also converges to its steady-state level. In this case, long-run inequality and growth are given by, from (22) and aggregating (19), respectively:[13]

$$\sigma^2 = \left(\nu^2 \varkappa^2 + \varrho^2\right) / \left(1 - \beta^2\right) \tag{24a}$$

$$1 + \gamma = a_3 \psi \chi \exp\left(\sigma^2 \left(\pi + \digamma + q\right)\right) \tag{24b}$$

where

$$q \equiv 0.5 \left(\alpha - 1\right) \left(\lambda + \left(1 - \alpha\right) \nu\right) < 0 \tag{25a}$$

$$\digamma \equiv 0.5 \beta \left(\beta - 1\right) < 0 \tag{25b}$$

$$\pi \equiv 0.5 \nu \left(\nu - 1\right) \varkappa^2 < 0 \tag{25c}$$

[13] Appendix A provides a detail on the derivation of the balanced growth path.

γ is the steady-state growth rate of the economy. The long-run equilibrium of the economy is a balanced growth path, with a constant non-zero level of inequality (see Appendix A).

Several important results follow from (24): First, steady-state inequality increases in IGE and volatility. Second, Proposition 3 also holds in the steady state. Third, inequality has a negative impact on long-run growth. This is easily seen as all the terms in the bracket in (24b) are negative. Finally, redistributive policy (sign of ω) impacts long-run growth directly, via its effect on agents' savings and effort, and indirectly, via the growth–inequality trade off.

5. Optimal redistributive policies

5.1. Growth maximizing policies

Should the government innovation policy be progressive or regressive to maximize growth?[14] For a homogeneous economy (especially, $h_{i0} = h_0$), the choice of ω is straightforward. In order to maximize growth, public R&D should be regressive ($\omega > 0$) and take the maximum attainable value because regressivity *only* promotes efficiency via agents' savings and effort decisions.

For the heterogenous case, however, this may not be necessarily true. The policy effect on growth could be rather nonlinear, as both inequality (σ^2) and ψ could increase in ω. On the one hand, a regressive R&D policy encourages growth due to

[14]Although our main focus here is on ω, note that both ω and τ are policy variables. With respect to τ, the growth maximizing tax rate (τ^*) could easily be computed from (24b): $\partial\gamma/\partial\tau \equiv \tau^* = \lambda/(\lambda + \upsilon)$, which is independent of redistribution, ω. τ^* reaches its upper bound when $\upsilon = 0$ – when there is, no, or, little private investment in R&D.

its positive impact on savings and effort; on the other, it has a negative impact on growth via the inequality–growth trade off.

Proposition 4. *(i) If $\sigma_0^2 = 0$, a regressive R&D policy unambiguously promotes growth. (ii) If $\sigma_0^2 \neq 0$ and $\varkappa^2 \neq 0$ (or $\varrho^2 \neq 0$), the long-run growth effect of ω is ambiguous.*

Proof. See Appendix C. ■

We can have further insight on the nonlinearity, if we specify parameter values that seem reasonable for real economies. We thus set the subjective discount factor ρ at 0.99, as in numerous macroeconomic studies. Following Benabou (2002), we set the intertemporal elasticity of substitution $\epsilon \equiv 1/(\eta - 1)$ to 0.20. The elasticity of substitution between intermediate goods is fixed at 6 (Kollmann, 2002). The initial knowledge (h_0) and the initial distribution of knowledge (σ_0^2) are normalized at unity. Getachew and Turnovsky (2015) consider a 0.4 standard deviation for the logarithm of idiosyncratic shocks. Based on that we set $\chi^2 = \varrho^2 = 0.16$.

Using the World Bank (2015) database for the period 2005-2014, the average public and private R&D spending GDP ratio is computed as 2.81% for the U.S.. The public R&D spending ratio (τ) is thus 0.548%. The parameter ν represents the elasticity of knowledge production with respect to private R&D spending. Following Jones and Williams (2000), we set $\nu = 0.5$. The value for the elasticity of public knowledge widely varies among empirical estimates.[15] We use Levy's (1990) estimate for the public investment elasticity of private R&D for nine OECD countries between 1963 and 1984, which is about 0.34 and consistent to the estimate's of

[15] See David et al. (2000) for the survey of the literature.

Leyden and Link (1991).[16] This implies $\theta = 0.16$. Finally, we calibrate a_1 to reproduce a 2%average annual growth rates of GDP. Table 1 summarizes the benchmark parameter values.

Table 1: Baseline values

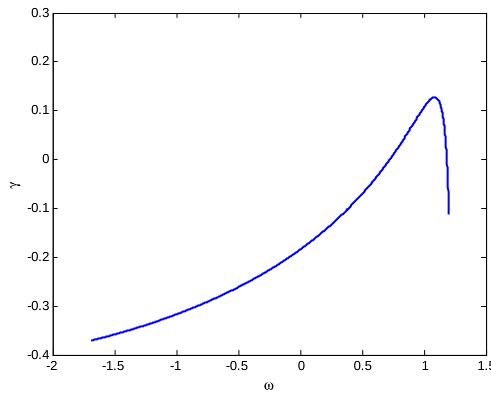
ρ	0.99
θ	0.16 (Levy, 1990)
ν	0.5 (Jones and Williams, 2000)
λ	$1 - \theta - \nu$
ϵ	0.2 (Benabou, 2002)
$\chi^2 = \varrho^2$	0.16 (Getachew and Turnovsky, 2015)
τ	0.548% WDI (2015)
a_1	0.0585 (Reprduces 2% annual growth rate)
ε	6 (Kollmann, 2005)

Applying these values to (24b), we find that the growth maximizing policy is quite regressive (see Fig. 3). Growth is in particular maximized when ω is slightly greater than unity, $\omega = 1.09$.[17]

[16]Leyden and Link's estimate is based on a 1987 data set of 137 R&D laboratories for the U.S. industries.

[17]Note that there is a restriction on ω for a stable inequality dynamics (22), $0 < \beta < 1$. Given our calibrated values, this means $-1.6961 < \omega < 1.2451$.

Figure 3: Growth Maximizing Redistributive R&D Policy



5.2. Welfare maximizing policies

While growth and inequality are important macroeconomic variables, the economic significance of any policy should be basically judged in terms of its impacts on social welfare. Given that $V_{i0} = \max U_{i0}$ is the discounted sum of individual welfare, its aggregation across the entire population leads to the discounted sum of aggregate welfare: $W_0 = \int_0^1 V_{i0} di$. Then, the steady-state aggregate welfare is given by (see Appendix B for details)

$$W = (1-\rho)^{-1} \left(\ln c_0 - 0.5\sigma_c^2 - l^\eta \right) + \rho / (1-\rho)^2 \ln (1+\gamma) \tag{26}$$

where

$$c_0 = (1-\tau)(1-b) y_0 = (1-\tau)(1-b) l a^{1/\alpha} h_0 \exp(0.5 (\alpha - 1) \sigma_0^2) \tag{27}$$

$$\sigma_c^2 = \chi^2 + \alpha^2 \sigma^2 \tag{28}$$

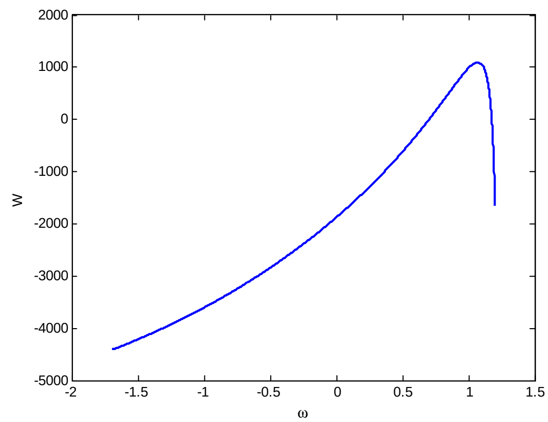
where c_0 and σ_c^2 are initial aggregate consumption and consumption inequality, respectively.

The first term in (26) captures the discounted initial aggregate welfare (at $t = 0$). Given that h_0 is predetermined, so is σ_0^2, which has a negative impact on welfare. Since individuals derive a negative utility from increased effort, the policy effects (ω) on the initial welfare is nonlinear. While a higher ω may negatively affect initial welfare via an effect on efforts and inequality, it may increase it through boosting initial income (higher y_0).

The second term in (26) comes from the economy-wide growth rate, which captures individuals' rewards for saving and investing in their future. In this case, any effect policy has on growth would directly pass to welfare. A higher ω unambiguously raises the steady state inequality, σ^2 as seen from (24a) and through this channel it lowers growth and hence welfare. On the other hand, it promotes investment and raises effort that could in turn raise growth and thus welfare.

Should the government R&D policy be progressive or regressive to maximize welfare? For reasonable parameter values, we see that welfare maximizing policy is also regressive due to a strong growth effects on aggregate welfare (see Fig. 4). Aggregate welfare is in particular maximized when $\omega = 1.07$, which is slightly less regressive than the case for growth due to an additional adverse effect of a regressive policy on initial welfare.

Figure 4: Welfare Maximizing Redistributive R&D Policy



6. How regressive is R&D in US states?

In Figure 1 we presented a stylized fact using state level US data that regional inequality is higher in the US where the intensity of R&D spending is higher. Our growth model gives rise to a testable hypothesis that the R&D programmes are more regressive in more unequal US states. In this section, we provide an estimate of regressivity of R&D (measured by ω) in each state based on our model results. We exploit two key equations of our model (namely (24a) and (21)) to back out ω from the regional Gini coefficient data for the US.

One computes ω from the model using the US state level GDP data as follows. Exploiting the lognormality property of our model, compute the mean to median ratio using the variance of $\ln y_{it}$. The steady state mean to median ratio of income

(m_y) is thus given by,

$$m_y = \frac{\exp(\mu_y + 0.5\sigma_y^2)}{\exp(\mu_y)} = \exp(0.5\sigma_y^2) \tag{29}$$

which implies that $\sigma_y^2 = 2\ln m_y$. Then, using the income equation (6), rewrite σ^2 in terms of σ_y^2:

$$\sigma^2 = \frac{\sigma_y^2 - \varkappa^2}{\alpha^2} \tag{30}$$

In the next step, using the social mobility equation (21), compute β:

$$\beta = \left[1 - \frac{\nu^2\varkappa^2 + \varrho^2}{\sigma^2}\right]^{0.5}$$

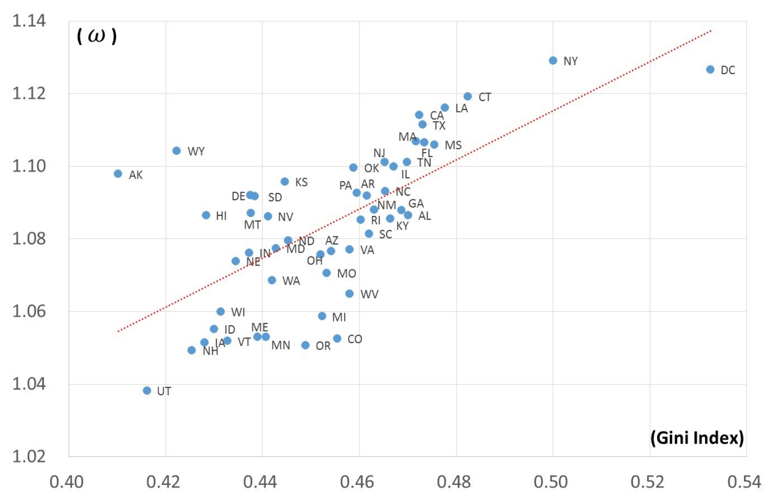
Finally, using (20b), compute ω:

$$\omega = \frac{\beta - \theta - \nu\alpha}{\lambda} \tag{31}$$

The annual median household income is available for each state, from the Bureau of Economic Analysis. However, there is no corresponding mean household income available. We, therefore, constructed a series for it by using per capita state income, population and the number of households in each state, which are all available in the Bureau of Economic Analysis website for the period 2005-2015. Multiplying the per capita income by population upon dividing it by the number of households, we generate a series for income per household data for each state over the sample period 2005-2015. We compute the time average of mean and median household income for computing the variance of log income using the formula (29). Following the steps above, we compute ω for each US state. While computing ω , we fix the rest of the parameters at the baseline levels as shown in Table 1.

Figure 5 plots the values for ω corresponding to each state against the five year average Gini index for the period 2007-11. The relationship is positive with a correlation coefficient of 0.66. US states with a higher inequality have more regressive R&D innovations.

Figure 5: Inequality and Regressvity of R&D Spending in US States



7. Is there a case for optimal progressive R&D policy?

As seen in Proposition 1, a negative ω depresses individual savings and effort. Thus, it adversely affects growth via its negative effects on private investment and labour supply although it has a positive effect on inequality and hence growth. However, a consumption tax and investment subsidy can be designed to correct some of these negative effects on private investment and restore it to a regime with *neutral*

R&D policy.

Let the government subsidizes individual savings (at a rate of ϑ) using a consumption tax. In this case, (7) becomes:

$$h_{it+1} = a_2 \zeta_{it+1} h_{it}^{\theta} \left(\left(1+\vartheta\right) s_{it} \right)^{\nu} g_{it}^{\lambda} \tag{32}$$

where ϑ is the subsidy rate. Therefore, the individual receives an additional amount of ϑs_{it} subsidy for s_{it} level of investment. If the government chooses to finance this with a consumption tax at a rate of τ_c, then individual and (the balanced) government budget constraints become respectively,

$$\left(1+\tau_c\right) c_{it} + s_{it} = \left(1-\tau\right) y_{it} \tag{33}$$

and

$$\vartheta s_t = \tau_c c_t \tag{34}$$

The rest of the government budget is given separately by (8). With consumption tax, only individual optimal consumption will be affected.

$$c_{it} = \left(1-b\right)\left(1-\tau\right) / \left(1+\tau_c\right) y_{it} \tag{35}$$

Since all individuals face the same consumption tax rate (τ_c) and investment subsidy rate (ϑ), the optimal individual saving rate and the labour supply remain the same as (13a) and (13b) respectively as in the case of no tax-subsidy. The optimal solution for consumption, however, decreases by a factor of $1/(1+\tau_c)$.[18]

Defining individual's *effective* savings as $\widetilde{s}_{it} \equiv (1+\vartheta)\, s_{it}$, which includes the subsidy, the government could restore individual investment to the regime of neutral innovation policy ($\omega = 0$) by setting the investment subsidy rate to:

$$\vartheta = -\rho\omega\lambda/(1-\rho\theta) \tag{36}$$

where $\vartheta > 0$ for $\omega < 0$. The corresponding consumption tax is then given by:[19]

$$\tau_c^* = \vartheta b/(1-b-\vartheta b) \tag{37}$$

This tax-subsidy scheme of the government has no effect on the households' optimal savings and labour supply decisions.[20] The effective saving rate is only elevated to the point where it replicates the neutral innovation scenario. In other words, the government can mitigate (at least part of) the adverse growth effect of a progressive innovation policy by designing a tax-subsidy scheme.

What happens to the steady state welfare due to this tax subsidy operation? Recall the expression for long run welfare (26). Note that this tax-subsidy scheme lowers inequality (σ_c^2), which promotes W_0. However, it also depresses c_0, which

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[18] More detailed derivations are available from the authors upon request.

[19] In deriving τ_c^*, first aggregate and then substitute (33) and (13a) into (34) to get

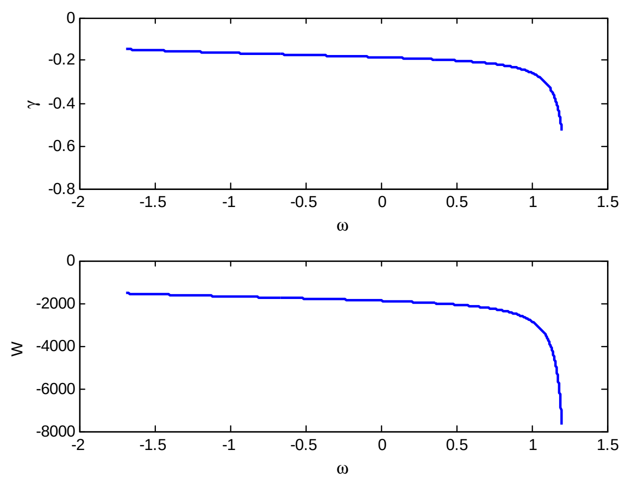
$$\tau_c/\vartheta = b(1+\tau_c)/(1-b)$$

which solves to (37).

[20] However, this may not be always the case, particularly, when applies to a more general utility function.

lowers W_0. More progressive innovation policy (more negative ω) has two opposing effects, positive growth effect and a negative tax distortionary effect. Such a trade-off allows for an optimal ω? For our baseline calibrated model, we find that the long run welfare is maximized at the lowest bound for ω which is -1.696 (see Fig 6).

Figure 6: Investment Subsidy and Optimal Progressive R&D Policy



One can indeed derive a closed form expression for optimal ω in this case. Since the lower bound for ω is set by highest social mobility ($\beta = 0$). From (21) it follows that the optimal ω is given by

$$\omega = -(\theta + \upsilon\alpha)/(1 - \rho\theta) \tag{38}$$

which upon substitution in (36) yields an expression for the optimal investment subsidy:

$$\vartheta = \frac{\rho(\theta + \upsilon\alpha)}{(1 - \rho\theta)} \tag{39}$$

Greater knowledge intensity (θ) and greater productivity of private investment (υ) mean higher investment subsidy.

It is important to understand that there is no free lunch in this optimal tax-subsidy scenario. The brunt of the distortion caused by progressive innovation is borne by consumption tax which lowers welfare but does not hurt productive efficiency because saving and labour supply decisions remain unaffected. This explains why the government could push progressivity to its maximum limit without hurting productive efficiency.

8. Conclusion

R&D policy has uneven impacts on the economy, a fact which has not been paid much attention in the literature. While regressive R&D policy could escalate economic inequality, it could promote growth through creating incentives. On the other hand, progressive R&D policy could benefit poor at the expense of long run growth. Our stylized facts suggest that in the US, R&D policy has significant regressive consequences while in SSA and other countries it is progressive in nature. In this paper, we develop a heterogenous-agent growth model with in-house R&D to understand these broad empirical regularities. In our model, growth and inequality are endogenously determined. We show that a regressive R&D policy unambiguously escalates economic inequality. Growth and welfare effects of such policy is nonlinear giving rise to an optimal degree of regressivity. Using US state level data, we back out the regressivity policy parameter from our model and find that the R&D policy in the US is indeed regressive in nature. We present a policy scenario of investment subsidy financed by consumption tax that could mitigate the painful trade off between efficiency and redistribution, leading to maximum progressiveness in R&D policy. A possible future extension of our study is to undertake a detailed econometric investigation of the role of public R&D policy in regional inequality in the US.

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Appendix

A. Aggregate wealth and growth dynamics

From (15), (17) and(18), all aggregate variables except aggregate knowledge grow at the same rate:

$$1 + \gamma_t \equiv y_{t+1}/y_t = g_{t+1}/g_t = c_{t+1}/c_t = \Omega_t h_{t+1}/h_t \tag{A.1}$$

where

$$\Omega_t \equiv \exp\left(0.5\left(1-\alpha\right)\left(\sigma_t^2 - \sigma_{t+1}^2\right)\right)$$

Note that (A.1) holds along the transitional dynamics where inequality evolves based on its own past history as in (22). In the steady state where $\sigma_{t+1}^2 = \sigma_t^2 = \sigma^2$, the economy will be in a balanced growth path (BGP) where $\gamma_t = \gamma$.

To derive the balanced growth rate, one needs to first derive the growth rate of aggregate knowledge during the transition by aggregating (19) to get the dynamics of aggregate knowledge as follows,

$$h_{t+1} = a_3 \psi \chi h_t^{\theta+\upsilon+\lambda} \exp\left(\sigma_t^2\left(\pi + F + q\right)\right)$$

where π, F and q are defined in (25). Then, given constant returns to scale in knowledge production, one obtains the steady state growth rate (24b).

B. Derivation of the steady state welfare

Note first that the discounted sum of individual welfare is simply $V_{i0} = \max U_{i0}$. Aggregating V_{i0} across the entire population leads to the discounted sum of aggregate welfare:

$$W_0 = \int_0^1 V_{i0} di$$

Then considering (11), we have

$$\begin{aligned} W_0 &= E_i E_0 \sum_{t=0}^{\infty} \rho^t \left(\ln c_{it} - l_{it}^{\eta}\right) \\ &= E_0 \sum_{t=0}^{\infty} \rho^t \left(\ln c_t - 0.5\sigma_{t,c}^2 - l^{\eta}\right) \end{aligned}$$

Then, the steady-state discounted expected aggregate welfare is given by,

$$\begin{aligned} W &= E_0 \sum_{t=0}^{\infty} \rho^t \left(\ln \left(c_0 \left(1+\gamma\right)^t\right) - 0.5\sigma_c^2 - l^{\eta}\right) \\ &= \rho / \left(1-\rho\right)^2 \ln\left(1+\gamma\right) + \left(\ln c_0 - 0.5\sigma_c^2 - l^{\eta}\right) / \left(1-\rho\right) \end{aligned}$$

where c_0 is given by, from (15) and (17),

$$c_0 = (1-\tau)(1-b) l a^{1/\alpha} h_0 \exp(d_0)$$

One applies similar procedures to derive the steady-state discounted expected aggregate welfare with consumption tax and investment subsidy (W'):

$$W' = \rho / \left(1-\rho\right)^2 \ln\left(1+\gamma\right) + \left(\ln c_0' - 0.5\sigma_c^2 - l^{\eta}\right) / \left(1-\rho\right)$$

where

$$c_0' = (1+\tau_c)^{-1}(1-\tau)(1-b)la^{1/\alpha}h_0\exp(d_0)$$

where ϑ and τ_c are given by (36) and (37), respectively.

C. Proof for Proposition 4

(i) If $\sigma_0^2 = 0$, which implies $h_{i0} = h_0$, then, from (19), $\sigma_1^2 = \sigma^2 = \nu^2\varkappa^2 + \varrho^2$. It is then straightforward to see γ increases in ω.

(ii) If $\sigma_0^2 \neq 0$ and $\varkappa^2 \neq 0$ (or $\varrho^2 \neq 0$), then from (19), $\sigma^2 = \nu^2\varkappa^2/(1-\beta^2)$ (or $\sigma^2 = \varrho^2/(1-\beta^2)$). In this case, both σ^2 and ψ increase in ω in (24b), leading to an ambiguous effect of ω on growth.

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