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IS THERE AN ENVIRONMENTAL RACE TO THE BOTTOM IN AN ENDOGENOUS GROWTH MODEL OF INTERJURISDICTIONAL COMPETITION?*

Sanghyun Hwang†

Department of Economics and Finance, Sangmyung University,
Seoul, 03016, Korea
shwang@smu.ac.kr.

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Abstract

This paper explores the impact of increasing capital mobility on regional growth and environment. I develop an endogenous growth model in which each local government competes against the others to induce mobile stock of capital into its region. Then I show that an increase in capital mobility generates "tax importing" due to which each locality experiences a higher growth rate and more degraded environment. That is, the increasing mobility dampens the capital tax and transfers the burden of pollution abatement to the locality. This finding supports the hypothesis of "race to the bottom" in environmental standards. Identifying a reduction in overall welfare of residents, I consider two alternative federal interventions in the model: uniform environmental standard and requirement of lump sum transfer (or tax). Both of these federal instruments enhance the residents' welfare.

Keywords: Endogenous Growth Model, Interjurisdictional Competition, Environmental Race to the Bottom
JEL Classification Codes: H77, O44, Q01, R11

I. *Introduction*

Compared to the past, economic interdependence has gradually increased in recent years. The stock of capital as a factor of production (e.g., factory or machinery) does not need to be invested in a particular region. Many regional economies have achieved successful economic growth with a higher capital mobility. But, many environmentalists are concerned that the regions with a rapid growth rate experience many localized environmental externalities. An example is deforestation. If a higher capital mobility generates severe interregional competition,

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† Department of Economics and Finance, Sangmyung University, 20, Hongjimun 2-gil, Jongno-gu, Seoul, Republic of Korea 03016. Email: shwang@smu.ac.kr.

less stringent local standards could deteriorate the local environments. However, the increasing capital mobility might give both a higher economic growth and a better environment, if each locality is concerned with its environmental externality and sets an environmental measure according to its own interest. Therefore, ones may be somewhat confused about how the increasing economic integration affects the local economic development and environment.

The literature on local public finance and environmental economics has given two opposite conclusions on the "race to the bottom" in environmental standards. This hypothesis states that severe economic competition among local authorities will result in lower levels of environmental quality. Thus, federal government intervention is necessary to preserve local environments. Markusen et al. (1995) show that noncooperative behaviors of two regions generate welfare loss in a model with an endogenous plant location. Kunce and Shogren (2005b) construct a competitive interjurisdictional model, and they suggest that devolved command-and-control environmental regulation is not efficient since local residents likely don't capture environmental rents from local production entirely. On the other hand, it is also argued that each local jurisdiction could achieve an efficient environmental regulation by itself. Using a simple static model with interjurisdictional competition, Oates and Schwab (1988) contend that the local setting of environmental standards is globally optimal in the jurisdictions homogenous in workers. Williams (2012) points out that cases in which state governments chose their own tighter regulations over federal environmental regulation in the U.S. have become more common in recent years, and he argues that this change occurred because the form of federal regulation shifted from command-and-control regulation toward more incentive-based regulation. More recently, with a model where two regions produce two goods and have interregional environmental damages, Ferrara et al. (2014) show that decentralization may cause environmental standards or taxes to be weaker or stricter, according to the degree of regional comparative advantage and the extent of transboundary pollution.

The purpose of this paper is to examine how the increasing capital mobility impacts regional economic growth and environment. To answer the question, I develop an endogenous growth model in which each local government competes against the others to induce imperfectly mobile stock of capital into its region. Then I form a conclusion on the hypothesis above. Comparing three alternative policy systems between a federation and local jurisdictions, this paper presents the welfare implication, and it suggests which policy structure is better for regional development and environment preservation with the increasing capital mobility.

This paper develops an endogenous growth model of interjurisdictional tax competition with local environments at an imperfect capital mobility. There each local government sets its capital tax rate competitively against the others to induce imperfectly mobile stock of capital into its region, and then it uses the capital tax to finance public expenditure on pollution abatement and lump sum transfer for its local residents. In this endogenous growth model, the technological change on labor productivity is incorporated as learning effects from investment activities as in Arrow (1962), and a public expenditure is used as the pollution abatement activity as in Smulders and Gradus (1996). Also, this paper uses the full range of capital mobility such that the stock of capital gets from perfectly immobile to perfect mobile, following the formulation of capital mobility as in Rauscher (2005), and it endogenizes all the federal and local policy variables in the model.

Hence this paper contributes to the literature on interjurisdictional competition and growth theory as follows. It extends the issues of fiscal or regulatory policy competition to a dynamic framework. Almost all previous studies have long employed static models to address the issues of decentralized environmental regulations (see Oates and Schwab, 1988; Markusen et al., 1995; Kunce and Shogren, 2002, 2005b, 2005a; Lapan and Sikdar, 2011; van't Veld and Shogren, 2012; Williams, 2012; and Ferrara et al., 2014). They do not consider dynamic features of capital as a stock variable. As the stock of capital accumulates over time, the amount of pollution with no abatement activities grows at a positive rate. For a local economy to have a perpetual growth with a stable level of environmental quality, some forms of abatement activities should be present.[1] Also, the accumulated stock of capital creates a positive externality on productivity growth in regional economies. In a particular region into which relatively more amounts of capital stock are induced, the local residents provide more productive labor supply to local production because of learning effects from investment activities of capital owners.

Second, the scope of previous literature is limited to distortion-inducing or efficiency-enhancing arguments with a fixed capital mobility as in Oates and Schwab (1988) and Kunce and Shogren (2005b). However, this adoption of capital mobility cannot analyze the impact of amalgamation on local policy variables, as if the economic integration had been increased. Moreover, in order to look at the implication of distortionary tax, the previous papers usually specify the policy instruments of an upper level of government as exogenous as in Zodrow and Mieszkowski (1986) and Rauscher (2005). But, an upper level of government could respond to the policies set by the lower levels of government in the real policy system, as is done in the United States.

The model of this paper derives the following results. The local jurisdictions with a full range of local policies (i.e. no federal intervention) achieve a sustainable economic development for a given level of capital mobility. However, an increase in capital mobility generates "tax importing" due to which each locality experiences a higher growth rate and more degraded environment. That is, the increasing mobility dampens the capital tax and transfers the burden of pollution abatement to the locality. The capital tax rate is negative and the local environment is deteriorated completely at the perfect capital mobility. This finding supports the hypothesis of "race to the bottom" in environmental standards.

In addition, this paper identifies that the increasing capital mobility reduces the overall welfare of residents although it raises a higher growth rate. To avoid the cut-throat competition and preserve regional environments, an upper level of government must intervene to save the single jurisdictions. An uniform environmental standard and a requirement of lump sum transfer (or tax) are considered as the federal interventions in this model. Both of two optimal interventions improve the residents' welfare. The optimal uniform environmental standard is independent of any capital mobility, so that it prevents local environment from degradation by the increasing capital mobility (or severe regional competition). However, the optimal transfer (or tax) requirement degrades the environmental quality more if the resident's elasticity of intertemporal substitution is less than one, even though it secures a consumption level for the local residents against the increasing capital mobility.

[1] The literature on the endogenous growth and environmental economics has addressed how an economy can achieve sustainable growth with a stable level of environmental quality. Bovenberg and Smulders (1995) develop a two sector endogenous growth model with pollution-augmenting technology that helps the pollution be used more effectively over time.

This theoretical prediction is entirely consistent with empirical findings by several recent studies. Using a data set of 19 OECD countries for 1981-2001, Garretsen and Peeters (2007) measure increased international capital mobility by FDI flows and then conclude that it implies a lower corporate tax rate. Bai et al. (2019) empirically find that inter-regional corporate income tax competition influences local environment negatively and makes the environmental quality get worse in spatially correlated regions as well, based on panel data of 30 Chinese provinces for 2004-2014. Woods (2021) observes the increasingly pervasive use of “No More Stringent” (NMS) laws in the American states, and he shows as an empirical result that interstate competition for mobile capital drives the diffusion of NMS laws, leading states to relax regulatory standards. So, Woods (2021) suggests the use of federal programs that states implement cooperatively.

The paper is organized as follows. In the next section, I present an endogenous growth model with interjurisdictional fiscal competition. Section 3 employs majority voting to solve for local decisions and then examines whether the local jurisdictions “race to the bottom or the top” in environmental standards. In section 4, two federal interventions are endogenized in the model. I investigate how the optimal interventions affect the local environmental quality and economic growth. The final section concludes and suggests future research.

II. *The model*

Assume that a federation consists of infinitely small identical jurisdictions, and each local jurisdiction has many atomistic profit-maximizing firms which take the role of local production. In the model, the federation is represented as a unit real plane $[0, 1] \times [0, 1]$ in which a firm i of a jurisdiction j is expressed as one specific point $(i, j) \in [0, 1] \times [0, 1]$. In each jurisdiction, two types of agents, called capitalist and worker, live on the infinite horizon. The members in each group are homogenous and large in number.[2] At each time, the capitalists can save but cannot work, while the workers consume all the earned incomes with no saving.[3] As local production factors, the capital stock that is a forgone consumption is imperfectly mobile, but the labor is immobile across jurisdictions.

1. Local environmental quality

The capital stock K_j invested in a local jurisdiction j generates pollution P_j through a production process. The pollution as an externality is ‘bad’ for the residents in the jurisdiction.[4] If a higher level of capital is located in the jurisdiction, the residents consume a lower level of local environmental quality. However, the local pollution can be reduced by public abatement

[2] Here, the workers are homogenous as wage earners. However, the paper extends the model to include non-wage workers whose circumstances and interests are different from those of wage workers.

[3] Judd (1985), Lejour and Verbon (1997), and Rauscher (2005) make this assumption.

[4] Local residents have disutility from pollution as a negative externality, so that the pollution is incorporated into the utility function. We could include the negative externality in the production function as well as the utility function, however. The pollution could have a negative effect on production if lower environmental quality creates less productivity as in Smulders and Gradus (1996) and Bovenberg and Smulders (1995). However, this aspect does not make any significant difference, even though this analysis does not consider it formally.

activities G_j which is financed with a tax on capital by the authority of the jurisdiction. If the jurisdiction decides on more public expenditure for abatement activities, the capital stock induced in the jurisdiction deteriorates the local environment less. Thus, the local environmental quality of jurisdiction j at each time is represented as the following pollution function

$$P_j=\left(\frac{K_j}{G_j}\right)^{\chi}, \tag{1}$$

where χ is a positive elasticity of pollution with respect to the capital-abatement ratio.[5] In eq. (1), the pollution is increasing in attracted stock of capital and decreasing in public abatement activities in jurisdiction j: $\partial P_j/\partial K_j>0$, $\partial P_j/\partial G_j<0$. Assume further that a polluting emission generated in one jurisdiction doesn't have a spillover effect on another. Therefore, the local environment is modeled as a purely public good that can be consumed within a particular jurisdiction.

2. Production technology

At each point in time $t\in[0, \infty)$, many atomistic profit-maximizing firms take the role of local production.[6] In order to produce a private good Y_{ij} that is sold in the national markets, each firm i in jurisdiction j employs stock of capital K_{ij} and labor L_{ij} and use the following form of production technology

$$Y_{ij}=Y(K_{ij}, L_{ij}, K_j)=AK_{ij}^{\alpha}L_{ij}^{1-\alpha}K_j^{1-\alpha}, \tag{2}$$

which exhibits conventional constant returns to scale in two factors of production, capital stock and labor. In eq. (2), the production technology is concave and strictly increasing in capital and labor, and shows the normal monotonicity: $\partial Y/\partial K_{ij}>0>\partial^2 Y/\partial K_{ij}^2$, $\partial Y/\partial L_{ij}>0>\partial^2 Y/\partial L_{ij}^2$, and $\partial^2 Y/\partial L_{ij}\partial K_{ij}>0$. Also, it satisfies the Inada conditions for the two arguments: $\lim_{K_{ij}\to 0} \partial Y/\partial K_{ij}=\lim_{L_{ij}\to 0} \partial Y/\partial L_{ij}=\infty$, and $\lim_{K_{ij}\to \infty} \partial Y/\partial K_{ij}=\lim_{L_{ij}\to \infty} \partial Y/\partial L_{ij}=0$.

In addition to the two production factors, the production function includes the aggregate level of capital stock K_j which implies a technological progress of jurisdiction j at each point in time t. The technological advance is considered as by-products when capitalists invest their stock of capital in the jurisdiction. Through the technological diffusion as a positive externality of capital stock, the local workers devote more effective labor to the local production and, in turn, get higher wages as in Arrow (1962).[7] Although it generates a negative environmental externality, the aggregate capital stocks K_j induced in the local production creates a positive externality on local workers' productivity. Like a pure public good within its boundary, the positive externality of one jurisdiction does not spill over to another. Hence, the level of labor efficiency differs across jurisdictions if the total amount of capital stock in the federation is distributed unevenly to each local jurisdiction over time.

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[5] The public expenditure G_j as pollution abatement activities as well as the pollution P_j are modeled as flow variables, e.g. filters used up within one period. Hence, in order to preserve a stable level of environmental quality, the public goods should be provided in each period. As in Acemoglu et al. (2012), modelling pollution or public abatement activities as stock values makes this analysis difficult without any critical different results along a balanced growth path.

[6] In order to reduce complication and save simplicity, the model omits the notation of time t on variable.

[7] This type of technological advance is 'labor-augmenting' as in learning-by-doing models.

3. Firms

Given a rental price of capital r_j and a wage rate w_j in the jurisdiction j, each competitive firm i has a profit flow $\pi_{ij}=L_{ij}(F(k_{ij}, K_j)-r_j k_{ij}-w_j)$ at each point in time, where the function $F(k_{ij}, K_j)=Ak_{ij}^{\alpha}K_j^{1-\alpha}$ shows constant returns to scale in the capital-labor ratio $k_{ij}:=K_{ij}/L_{ij}$ and the aggregate capital stock K_j. A single firm is so small that its own contribution to the aggregate capital stock of the jurisdiction is negligible. Hence, taken the technological progress in the jurisdiction K_j as parametric and using the zero-profit condition, the firms' profit maximization gives the rental price of capital and the wage rate where $r_j=\partial F(k_{ij}, K_j)/\partial k_{ij}$ and $w_j=F(k_{ij}, K_j)-k_{ij}\partial F(k_{ij}, K_j)/\partial k_{ij}$. Hence, the capitalists who invest their stock of capital into jurisdiction j earn a rate of return r_j equal to the marginal product of capital, and the workers who reside in the jurisdiction receive a wage rate w_j equal to marginal product of labor at each time t.

In each jurisdiction j, the aggregate level of capital stock and labor supply are $K_j=\int_0^1 K_{ij}\,\mathrm{d}i$ and $L_j=\int_0^1 L_{ij}\,\mathrm{d}i$, respectively. Assume that the workers in a jurisdiction supply their labors inelastically and normalize the aggregate labor supply L_j to one. Since in equilibrium, all firms in a jurisdiction choose the same levels of capital and labor, $L_{ij}=L_j=1$ and $k_{ij}=K_j$ for each i, the equilibrium rental price of capital and the equilibrium wage rate of jurisdiction j is as follows:[8]

$$r_j=\alpha A \tag{3}$$

$$w_j=(1-\alpha)AK_j \qquad \text{for any } j. \tag{4}$$

The wage rate received by the local workers in jurisdiction j is increasing in the amount of capital stock attracted in the jurisdiction, whereas the rental price of capital is constant over time. Thus, in order to raise the wage rate of its workers as actual residents, each local government competes against the rest to induce the scarce capital stocks of the federation by using its policy variables at each time.

4. Capital mobility

Taking a rental price r_j and a tax rate of capital τ_j, in jurisdiction j as given, a representative capitalist who plans to invest his stock of capital in jurisdiction j chooses a time path of consumption $\{C_{cj}\}_{t=0}^{\infty}$ to maximize his discounted life-time utility

$$\int_0^{\infty} e^{-\rho t}\frac{C_{cj}^{1-\varepsilon}-1}{1-\varepsilon}\mathrm{d}t \tag{5}$$

subject to his flow budget constraint

$$C_{cj}+\dot{K}_j=(r_j-\tau_j)K_j, \tag{6}$$

where a dot above a variable indicates the time derivative. The two parameters ε and ρ stand

[8] In equilibrium, $L_j=\int_0^1 L_{ij}\,di=L_{ij}=1$ and in turn, $K_j=\int_0^1 K_{ij}\,di=K_{ij}=L_{ij}k_{ij}=k_{ij}$ for all t.

for a constant relative risk aversion (or inverse of elasticity of intertemporal substitution) and a rate of time preference of the capitalist respectively. In eq. (5), the instantaneous utility function of capitalist does not include the pollution generated in jurisdiction j (or the environmental quality of the jurisdiction). Because a regional environment is modeled as pure public good that can be consumed only within a particular region, the capitalist whose domicile is not the jurisdiction j need not be concerned about environmental quality of the jurisdiction when he invests his capital stock in the region. Even though his home is in the jurisdiction j as his capital location, the capitalist does not have to care about the environmental quality. Since he is able to separate his own stock of capital physically and spatially, the capitalist can leave the jurisdiction j with no relocation of the capital stocks.[9]

Inserting the rental price of capital of jurisdiction j in eq. (3), the maximization problem of the representative capitalist yields the capital accumulation equation in jurisdiction j in equilibrium

$$\dot{K}_j=(1/\varepsilon)(\alpha A-\tau_j-\rho)K_j, \tag{7}$$

when the capital stock is perfectly immobile.[10] However, in the context of interjurisdictional competition, the accumulation equation has to be modeled as a mobility of capital stock. As in Rauscher (2005), the capital mobility term is augmented in eq. (7) as follows:

$$\dot{K}_j=(1/\varepsilon)(\alpha A-\tau_j-\rho)K_j+\phi(\alpha A-\tau_j-r_f)\psi(K_j,\ K_f), \tag{8}$$

where $K_f=\int_0^1 K_j\, dj$ is the total amount of capital stock, and r_f is denoted as a rate of return in the federation for each point in time.[11] In eq. (8), the second term shows a parameter $\phi\in[0,\ \infty)$ that measures a degree of capital mobility. If ϕ is zero, then capital stock is immobile across jurisdictions, and thus, eq. (8) reduces to eq. (7). The larger the parameter ϕ is, the more increased the capital mobility is. If ϕ tends to infinity, capital stock gets perfect mobility across jurisdictions. The size of investment flow is represented as a function $\psi(K_j,\ K_f)$ which is increasing in the capital stocks K_j in the jurisdiction itself and total capital stocks K_f in the federation. Further, the function ψ is assumed to be homogenous of degree one such that $\psi(K,\ K)=K$. Thus, a jurisdiction j can induce outside capital stocks into its region by cutting its capital tax rate, since the net rate of return in the jurisdiction is greater than in the rest ($\alpha A-\tau_j>r_f$).[12] Furthermore, the lower capital tax rate also raises the investment within the

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[9] Actually, the model assumption of 'infinitesimal' local jurisdictions gives zero probability on the event that a domicile and a investment location of a capitalist is identical.

[10] The Hamiltonian of the representative capitalist reads: $H_c(C_{cj},\ K_j,\ \nu_j)=(C_{cj}^{1-\varepsilon}-1)/(1-\varepsilon)+\nu_j((r_j-\tau_j)K_j-C_{cj})$. Differentiating this yields the first-order conditions with respect to the consumption C_{cj}, the capital stock K_j: $C_{cj}^{-\varepsilon}=\nu_j$ and $r_j-\tau_j=\rho-\dot{\nu}_j/\nu_j$. The first two conditions with eqs. (3) and (4) give the consumption growth rate of capitalist: $\dot{C}_{cj}/C_{cj}=(\alpha A-\tau_j-\rho)/\varepsilon$. For a growth path to be balanced, the net rate of return of capital, $\alpha A-\tau_j$, the capital tax rate τ_j should be constant over time. Thus, using the budget constraint in eq. (6) together with the consumption growth rate, it is shown that the capital and consumption grow at a same rate on the balanced growth path, and we arrive at eq. (7).

[11] As mentioned by Rauscher (2005), this formulation for capital mobility is intuitive and reasonable, whereas it is not derived explicitly by capitalists' profit-maximizing behavior. But, the formulation is easily applicable for analyzing the impact of the increased capital mobility. Of course, there are other specifications as in Lejour and Verbon (1997) and Hayashi (1982). But, the specifications seem to be not tractable or too complicated for the analysis. See Rauscher (2005) for more discussion and details.

jurisdiction as seen in the first term in eq. (8). Since an increase in capital stock yields a higher wage rate for workers in eq. (4), local jurisdictions have incentives to reduce their capital tax rate to attract the capital stocks of the federation.

5. Local residents

At each point in time, the infinitely-lived workers have utility from consumption C_{wj} but disutility from polluting emission P_j in a jurisdiction j as taken the life-time utility function

$$W=\int_0^\infty e^{-\delta t}U(C_{wj}, P_j)\mathrm{d}t \tag{9}$$

and the instantaneous utility function

$$U(C_{wj}, P_j)=\begin{cases}\dfrac{(C_{wj}P_j^{-\eta})^{1-\sigma}-1}{1-\sigma} & \text{for } 0<\sigma<1,\ \sigma>1\\ \ln C_{wj}-\eta\ln P_j & \text{for } \sigma=1\end{cases}. \tag{10}$$

In eq. (9), the parameter δ denotes the rate of time preference of worker. In eq. (10), two parameters σ and η represents the inverse of intertemporal substitution and the weight for pollution respectively.[13] Generally, the rate of time preference and the inverse of intertemporal substitution for the workers need not be the same as for the capitalists (i.e. $\delta\neq\rho$ and $\sigma\neq\varepsilon$). Eq. (10) says that the instantaneous function is strictly concave and increasing in private consumptions: $\partial U/\partial C_{wj}>0>\partial^2 U/\partial C_{wj}^2$. But, it is decreasing in the pollution generated in the jurisdiction j: $\partial U/\partial P<0$. Furthermore, it satisfies the Inada conditions for consumption and environmental quality: $\lim_{C_{wj}\to 0} U_C=\lim_{P_j\to\infty} U_P=\infty$, and $\lim_{C_{wj}\to\infty} U_C=\lim_{P_j\to 0} U_P=0$.[14]

To preserve a stable level of environmental quality, the authority of jurisdiction j finances the public abatement activity G_j with the tax revenue $\tau_j K_j$ collected from capital stock induced in the jurisdiction. Then the net of tax revenue (or a tax if it is negative), $T_j=\tau_j K_j-G_j$, is distributed equally to all workers in the jurisdiction. Thus, each worker's income consists of a wage rate w_j in eq. (4) and the tax revenues T_j at each point in time t. The flow budget constraint for a representative worker is

$$\begin{aligned}C_{wj}&=w_j+T_j \\ &=(1-\alpha)AK_j+(\tau_j K_j-G_j).\end{aligned} \tag{11}$$

Since the entry of more capital increases the wage rate of worker, each local jurisdiction has an incentive to reduce its capital tax rate against the rest of the federation to attract more mobile stock of capital. But, this lower capital tax rate can cause the jurisdiction to provide a lower

[12] However, the after-tax rental price of capital in the jurisdiction j is equal to the rate of return in the rest of federation in equilibrium, i.e. $\alpha A-\tau_j=r_f$.

[13] For a balanced growth path to be optimal, an instantaneous utility function is required to be an isoelastic form.

[14] In this model, the inverse of a pollution level is equivalent to a level of environmental quality. Thus, zero pollution level that implies no production in the jurisdiction is equivalent to the infinite level of environmental quality. Substitute the pollution function (1) into the instantaneous utility function (10) to rewrite the following utility function of consumption and environmental quality: $U^*(C, G/K)=(C^{1-\sigma}(G/K)^{\chi\eta(1-\sigma)}-1)/(1-\sigma)$. Then the Inada condition for environmental quality is $\lim_{G/K\to 0} U^*_{G/K}=\infty$ and $\lim_{G/K\to\infty} U^*_{G/K}=0$. This requires the condition: $\chi\eta(1-\sigma)-1<0$.

level of public good for pollution abatement, and thus, the local environment of the jurisdiction can be more degraded.

III. *Local outcomes with a full range of policies*

This section examines the local setting with a full set of policy variables under no federal intervention. In other words, each single jurisdiction determines, as its own policy instruments, a capital tax rate and a level of local environmental quality.

1. Political mechanism

In order to investigate how an increased capital mobility impacts the local setting of policies instruments, and in turn, on the growth performance, the preservation of local environment, and welfare implication, the paper adopts a majority-voting model as in Oates and Schwab (1988). It is assumed further that capitalists who live in a particular jurisdiction vote with their feet as in Tiebout (1956) and Rauscher (2005). The capitalists can reflect their preferences and interests on local political issues by leaving the jurisdiction, because they are perfectly mobile in the sense that their own capital stocks can be physically and spatially separated from themselves. The capitalists need not choose a jurisdiction both for a home and an investment place. No matter where they reside, they can relocate the capital stocks in any regions. Thus, the capitalists are assumed not to participate in any local political issues in this model. However, workers have to live where they work. The labor as a factor of production is not physically and spatially divisible from the workers. Consequently, the workers become actual residents in a particular jurisdiction by participating in the local political procedure, and thus, the local government reflects only workers' interests.[15]

2. Sustainable development

Since all workers are homogenous in a jurisdiction, the outcome of a median voter is that of the maximization problem of the representative worker. In each jurisdiction j, a representative worker chooses a time path of capital tax rate, and public abatement good to maximize the discounted life-time welfare (9) subject to the flow budget constraint (11), and the accumulation equation of capital stock invested into the jurisdiction (8), given the initial amount of capital stock $K(0)$. The current-value Hamiltonian for the maximization problem of the representative worker reads

$$H_w(\tau_j, G_j, K_j, \mu_j) = U((1-\alpha)AK_j + (\tau_j K_j - G_j), P_j) + \mu_j\left(\left(\frac{1}{\varepsilon}\right)(\alpha A - \tau_j - \rho)K_j + \phi(\alpha A - \tau_j - r_f)\psi(K_j, K_f)\right), \quad (12)$$

where μ_j denote the costate variable associated with the accumulation equation of capital stock

[15] On the static model with interjurisdictional competition for a limited amount of capital stock in a federation, Oates and Schwab (1988) consider workers with no capital stocks as the residents of a particular jurisdiction.

invested in jurisdiction j (or the shadow price of capital stock).

The ex-post equilibrium conditions are given by

$$r_f = \alpha A - \tau, \tag{13}$$

$$\phi(K, K_f) = K, \tag{14}$$

since all identical jurisdictions choose the same levels of endogenous variables: $\tau_j = \tau$, $G_j = G$, $K_j = K$, $C_{wj} = C_w$, and $\mu_j = \mu$ for all j.[16] Then the current-value Hamiltonian (12) and eqs. (13) and (14) require the following first-order conditions with respect to the capital tax rate τ, the public abatement good G, the capital stock K, and the costate variable μ in equilibrium:

$$U_C = \mu(1/\varepsilon + \phi), \tag{15}$$

$$U_C = -\chi \frac{P}{G} U_P, \tag{16}$$

$$((1-\alpha)A + \tau)U_C + \chi \frac{P}{K} U_P + \mu(\alpha A - \tau - \rho)/\varepsilon = \delta\mu - \dot{\mu}, \tag{17}$$

$$\dot{K} = (1/\varepsilon)(\alpha A - \tau - \rho)K. \tag{18}$$

The first two conditions above represent static allocation. Eq. (15) states that the marginal utility of consumption equals the shadow price of capital stock multiplied by the sum of the inverse of elasticity of intertemporal substitution for capitalist and the capital mobility. In eq. (16), in terms of utility, the marginal cost of public abatement good (the marginal utility of consumption) equals its marginal benefit, which is the reduction in pollution. It can be expected that reducing the capital tax rate, an increase in capital mobility reduces the consumption from eq. (15) and the public abatement good as well from eq. (16). The other two conditions above stand for dynamic allocation. After it is divided by μ, eq. (17) states that the marginal benefit of capital stock induced in the jurisdiction, its marginal cost (the increase in pollution) and the growth rate amount to the rate of time preference for worker and the rate of change in the shadow price of capital stock.

An additional condition that the optimal paths have to satisfy is the transversality condition

$$\lim_{t\to\infty} e^{-\delta t}\mu(t)K(t) = 0, \tag{19}$$

which guarantees that the consumption C_w and the capital stock K remain bounded at infinity.[17]

Eq. (16) can be rewritten as

$$\frac{G}{K} = \chi\eta \frac{C_w}{K}. \tag{20}$$

Eq. (20) shows that under a full set of policy instruments, each local jurisdiction efficiently provides its environmental quality as local public good since the marginal utility of

[16] In equilibrium, $K_f = \int_0^1 K_j dj = K\int_0^1 dj = K$ since $K_j = K$ for all j. Thus, the federal level of capital stock of the federation is the same as that of any jurisdiction: $K_f = K = K_j$ for all j. This fact together with the assumption that ϕ is homogenous of degree implies that $\phi(K_j, K_f) = \phi(K, K) = K$.

[17] This condition is necessary for the representative worker's problem if her instantaneous utility is bounded.

consumption is equal to the marginal utility of abatement.

Taking log and differentiating eq. (15) with respect to time and substituting this result together with eqs. (15) and (16) into eq. (17), we get the Keynes-Ramsey rule

$$\frac{\dot{C}_w}{C_w}=\left[\left(A-\frac{G}{K}-\rho\right)/\varepsilon+\phi\left((1-\alpha)A+\tau-\frac{G}{K}\right)-\delta\right]/\sigma+\eta(1-1/\sigma)\frac{\dot{P}}{P} \tag{21}$$

which describes the optimal consumption of the workers in each jurisdiction over time for a given capital mobility. The last term of eq. (21) disappears, if the level of pollution is constant over time (that is, the capital stock K and public abatement activity G grow at a same rate) or an intertemporal elasticity of substitution $1/\sigma$ equals unity). The term $(A-G/K-\rho)/\varepsilon+\phi((1-\alpha)A+\tau-G/K)$ represents the rate of return to capital stock induced to each jurisdiction with respect to the point of worker's view. The rate of return to capital is divided by two terms. The first term $(A-G/K-\rho)/\varepsilon$ is the rate of return at zero capital mobility while the second term $\phi((1-\alpha)A+\tau-G/K)$ is the rate of return at a positive capital mobility which implies an externality of mobile stock of capital across jurisdictions. Given a constant level of pollution, the consumption growth rate of local worker is positive, zero, or negative if the rate of return to capital is larger than, equal to, or smaller than the rate of time preference for the worker. In addition, all other things being unchanged, the worker's consumption grows faster for an elasticity of intertemporal substitution smaller than one if the growth rate of pollution is larger. In the opposite case, the consumption grows slower for either of an intertemporal elasticity larger than unity or a negative growth rate of pollution.

Next, it is shown that all variables grow at a constant rate γ along a balanced growth path. By taking logs and differentiating eq. (20) with respect to time, the consumption C_w and the public abatement activity G grow at the same rate. For the growth path to be balanced, the rate of return to capital in the federation is constant over time, and in turn, the capital tax rate τ is constant over time. Then substitute the ratio of consumption relative to capital from eq. (20) into the flow budget constraint of worker (11), and take logs and differentiate with respect to time to imply that the capital K and the abatement activity G grow at the same rate. Consequently, the transfer of net tax revenues T and the capital K grow at the same rate. Since the ratio of abatement relative to capital are constant, pollution P is constant as well. Thus, along a balanced growth path equilibrium, the stock of capital K, the consumption C_w of workers, and the abatement activities G of local government grow at the positive constant rate γ, but the capital tax rate τ and the pollution amount P grow at a zero rate:[18]

$$\dot{\tau}=\dot{P}=0, \tag{22}$$

$$\gamma:=\frac{\dot{K}}{K}=\frac{\dot{C}_w}{C_w}=\frac{\dot{G}}{G}=\frac{\dot{T}}{T}=(\alpha A-\tau-\rho)/\varepsilon. \tag{23}$$

[18] It is obvious that modeling pollution as a flow variable gives a simplified framework, but it does not modify the qualitative results along a balanced growth path. If the local environment of each jurisdiction were modeled as a renewable resource as in Bovenberg and Smulders (1995), pollution could not grow over time, since it should not exceed the regeneration capacity of natural environment for a balanced growth path to be sustainable. This is in accordance with the formulation of this model. In order to stabilize pollution, an endogenously growing jurisdiction can provide an increasing number of public abatement activities.

Proposition 1 (sustainable growth). *Given a capital mobility $\phi \in [0, \infty)$, each local jurisdiction achieves sustainable growth with a stable level of local environmental quality. That is, the growth rate of workers' consumption is positive, while the growth rate of regional pollution is zero over time.*

3. The impact of increased capital mobility

To characterize the outcome of local setting of policy instruments and analyze the impact of increased capital mobility in a simplified framework, denote the abatement and the consumption relative to capital as fundamental variables that are constant on the balanced growth path as $g := G/K$ and $c := C/K$. In addition,

Definition 1. Let a function $\Delta_\phi : \mathbb{R}_+ \to (0, 1]$ be defined as

$$\Delta_\phi(x) = \frac{x}{\varepsilon\phi + x},$$

which is decreasing in ϕ, and has the upper bound of unity, $\Delta_0(x) = 1$, at the zero mobility and the lower bound of zero, $\Delta_\infty(x) = \lim_{\phi\to\infty} \Delta_\phi(x) = 0$, at the perfect mobility respectively for any positive value $x \in \mathbb{R}_+ := (0, \infty)$.

Then eqs. (11), (20), (21), (22), and (23) give the reduced forms of solutions as follows:[19]

$$\gamma = \frac{A - \rho - (1+\chi\eta)\bar{c}_w \Delta_\phi(\kappa)}{\varepsilon}, \quad (\textit{growth rate}) \tag{24}$$

$$\tau = -(1-\alpha)A + (1+\chi\eta)\bar{c}_w \Delta_\phi(\kappa), \quad (\textit{capitaltax rate}) \tag{25}$$

$$g = \chi\eta\bar{c}_w \Delta_\phi(\kappa), \quad (\textit{public abatement}) \tag{26}$$

$$c_w = \bar{c}_w \Delta_\phi(\kappa), \quad (\textit{consumption}) \tag{27}$$

where the parameter κ and the consumption-capital ratio $\bar{c}_w$ at zero mobility ($\phi = 0$) are denoted as

$$\bar{c}_w := \frac{\varepsilon\delta - (1-\sigma)(A-\rho)}{\kappa} \quad \text{and} \quad \kappa := 1 - (1+\chi\eta)(1-\sigma).$$

The following lemma states that this model requires two inequalities for positive growth rate

[19] The original solutions for the growth rate γ, the capital tax rate τ, and the ratio of public abatement g and the consumption c_w relative to capital have the following reduced forms:

$$\begin{cases} \gamma = \left(A - \rho - \dfrac{(1+\chi\eta)(\delta - (1-\sigma)(A-\rho)/\varepsilon)}{\phi + 1 - (1+\chi\eta)(1-\sigma)/\varepsilon}\right)/\varepsilon, \\ \tau = -(1-\alpha)A + \dfrac{(1+\chi\eta)(\delta - (1-\sigma)(A-\rho)/\varepsilon)}{\phi + (1-(1+\chi\eta)(1-\sigma))/\varepsilon}, \\ g = \dfrac{\chi\eta(\delta - (1-\sigma)(A-\rho)/\varepsilon}{\phi + (1-(1+\chi\eta)(1-\sigma))/\varepsilon}, \\ c_w = \dfrac{\delta - (1-\sigma)(A-\varrho)/\varepsilon}{\phi + (1-(1+\chi\eta)(1-\sigma))/\varepsilon} \end{cases}$$

from eqs. (11), (20), (21), (22), and (23).

and bounded utility respectively. In Lemma 1, the term 'sustainability' means that for arbitrary $\phi\in[0, \infty)$, the growth rate is positive over time.

Lemma 1. *Suppose this endogenous growth model satisfy the following two inequalities:*

$$A>\varepsilon\delta(1+\chi\eta)+\rho \quad \text{and} \quad \sigma>1-\frac{\varepsilon\delta}{A-\rho}. \tag{28}$$

Then (i) $A-\rho>0$ *and* $\kappa>0$, *and in turn*, (ii) *the sustainability and transversality conditions are satisfied.*

Proof. See Appendix A. □

The next thing we do is to investigate the impact of an increase in capital mobility on regional growth and environment. Differentiating the growth rate γ in eq. (24) and the abatement-capital ratio g in eq. (26) with respect to the parameter ϕ of capital mobility yields

$$\frac{d\gamma}{d\phi}=-\frac{(1+\chi\eta)\bar{c}_w}{\varepsilon}\cdot\frac{d\Delta_\phi(\kappa)}{d\phi}>0,$$

$$\frac{dg}{d\phi}=\chi\eta\bar{c}_w\cdot\frac{d\Delta_\phi(\kappa)}{d\phi}<0,$$

since Δ is decreasing in ϕ by Definition 1. Thus, the growth rate γ is positively related to ϕ while the abatement-capital ratio g is negatively related to ϕ. Moreover, the capital tax rate τ becomes negative in eq. (25) and the abatement-capital ratio g is zero in eq. (26), as the stock of capital is perfectly mobile ($\phi\to\infty$). That is,

$$\begin{aligned}\lim_{\phi\to\infty}\tau&=\lim_{\phi\to\infty}[-(1-\alpha)A+(1+\chi\eta)\bar{c}_w\Delta_\phi(\kappa)]\\&=-(1-\alpha)A+(1+\chi\eta)\bar{c}_w\Delta_\infty(\kappa)=-(1-\alpha)A<0,\\\lim_{\phi\to\infty}g&=\lim_{\phi\to\infty}\chi\eta\bar{c}_w\Delta_\phi(\kappa)=\chi\eta\bar{c}_w\Delta_\infty(\kappa)=0.\end{aligned}$$

The increased capital mobility gradually reduces the capital tax rate. Note that each local economy has an infinite amount of pollution at $g=0$. Even if it positively affects the growth of local workers' consumption, the capital mobility gives a negative effect on local environment. Hence the increase in capital mobility generates a trade-off between a higher growth rate and a lower environmental quality to local jurisdictions.

To investigate the effect of increased capital mobility on the welfare of residents, the life-time welfare function (9) is integrated with respect to time as follows:

$$W=\begin{cases}\dfrac{1}{1-\sigma}\left[\dfrac{K(0)^{1-\sigma}(c_w)^{1-\sigma}P^{-\eta(1-\sigma)}}{\delta-\gamma(1-\sigma)}-\dfrac{1}{\delta}\right] & \text{for } 0<\sigma<1,\ \sigma>1\\[2ex] \dfrac{1}{\delta}\ln K(0)+\dfrac{1}{\delta}\ln c_w-\dfrac{1}{\delta}\eta\ln P+\dfrac{1}{\delta^2}\gamma & \text{for } \sigma=1\end{cases}. \tag{29}$$

Plugging the growth rate (24), the abatement-capital ratio (26), and the consumption-capital ratio (27) into eq. (29) gives the present value of the workers' welfare as

$$W=\begin{cases}\dfrac{1}{1-\sigma}\left[\left((1-\sigma)\overline{W}+\dfrac{1}{\delta}\right)\Delta_{\phi}(1)\Delta_{\phi}(\kappa)^{-\kappa}-\dfrac{1}{\delta}\right] & \text{for } 0<\sigma<1,\ \sigma>1\\ \dfrac{1}{\delta}[\delta\overline{W}+(1+\chi\eta)(\ln\Delta_{\phi}(1)-\Delta_{\phi}(1)+1)] & \text{for } \sigma=1\end{cases},\ (\textit{welfare}) \qquad (30)$$

where $(1-\sigma)\overline{W}+1/\delta=\varepsilon K(0)^{1-\sigma}(\bar{c}_w)^{-\sigma+\chi\eta(1-\sigma)}(\chi\eta)^{\chi\eta(1-\sigma)}>0$ for $0<\sigma<1$ and $\sigma>1$, and $\delta\overline{W}=\ln K(0)+\chi\eta\ln\chi\eta+(1+\chi\eta)(\ln\varepsilon\delta-1)+(A-\rho)/\varepsilon\delta$ for $\sigma=1$. Differentiating eq. (30) gives

$$\frac{dW}{d\phi}=-\frac{((1-\sigma)\overline{W}+1/\delta)(1+\chi\eta)\varepsilon^2}{\kappa}\cdot\phi\Delta_{\phi}(1)^2\Delta_{\phi}(\kappa)^{1-\kappa}<0.$$

The life-time welfare of workers is decreasing in capital mobility. The results are summarized formally in

Proposition 2 (full set of local policies). *Suppose that the capital mobility ϕ is increased. Then the growth rate γ increases, but the abatement-capital ratio g decreases in each local jurisdiction. Moreover, the capital tax rate τ becomes negative, and the deterioration of the environment is complete with the perfect mobility of capital. The increased capital mobility reduces the residents' welfare W.*

"Tax importing" dominates the growth effect as the capital stock becomes more mobile. Even though it provides local jurisdictions with a higher growth rate, the increased capital mobility transfers the burden of pollution abatement from capitalists to workers in each jurisdiction. The higher capital mobility prevents the jurisdiction from taxing on capital, and it reinforces their "race to the bottom" in the environmental standards.

To see an intuition more behind Proposition 2, consider a specific case where all the local residents don't care environmental pollution in each jurisdiction. Then Proposition 2 can still hold even without environmental pollution ($\eta=0$) as follows. If $\eta=0$, the first derivatives of γ and g in eqs. (24) and (26) with respect to ϕ become

$$\frac{d\gamma}{d\phi}=-\frac{\bar{c}_w}{\varepsilon}\cdot\frac{d\Delta_{\phi}(\sigma)}{d\phi}>0,$$

$$\frac{dg}{d\phi}=0,$$

and, as $\phi\to\infty$, τ and g in eqs. (25) and (26) become

$$\lim_{\phi\to\infty}\tau=\lim_{\phi\to\infty}[-(1-\alpha)A+\bar{c}_w\Delta_{\phi}(\sigma)]$$

$$=-(1-\alpha)A+\bar{c}_w\Delta_{\infty}(\sigma)=-(1-\alpha)A<0,$$

$$\lim_{\phi\to\infty}g=\lim_{\phi\to\infty}0=0.$$

Moreover, if $\eta=0$, the first derivative of W in eq. (30) with respect to ϕ becomes

$$\frac{dW}{d\phi}=-\frac{((1-\sigma)\overline{W}+1/\delta)\varepsilon^2}{\sigma}\cdot\phi\Delta_{\phi}(1)^2\Delta_{\phi}(\sigma)^{1-\sigma}<0.$$

Thus, the growth rate γ is increasing in the capital mobility ϕ, and the capital tax rate τ

becomes negative with the perfect mobility of capital. The abatement-capital ratio g is zero for all levels of capital mobility, which means that the deterioration of the environment is always complete regardless of capital mobility. Moreover, the increased capital mobility reduces the residents' welfare W. Hence Proposition 2 can have the following intuition in this case. An increase in capital mobility intensifies the tax competition among different jurisdictions, which reduces the capital tax. Then the transfer from capitalists to workers decreases, causing the reduction in workers' consumption and welfare.

IV. *Federal interventions*

If the federation does not intervene in the local setting, an increase in capital mobility gradually degrades local environments and reduces the residents' welfare. Hence, the next two subsections explore alternative federal policies that keep the residents' welfare at a higher level against the increased mobility of capital.

1. Uniform environmental standard

The competing jurisdictions with no federal mediation suffer from lower environmental quality as the stock of capital gets more mobile. To save the regional environments from deterioration, a federation has an incentive to set a uniform environmental standard for the local jurisdictions.[20] Hence this subsection examines how a higher level of government sets the uniform standard for lower levels of government. At the beginning of time, the federal government considers a particular amount of pollution for local environments such that $P_f = P_j$ for all j and any t. Then the uniform environmental standard can be defined by a public abatement activity G_j relative to capital K_j induced into each jurisdiction j:

$$\zeta := \frac{G_j}{K_j} = \left(\frac{1}{P_f}\right)^{1/\chi}. \tag{31}$$

Suppose the federal government gives an environmental guideline ζ to the local governments. Then each jurisdiction sets a capital tax rate as its own policy instrument. Thus backward induction characterizes an optimal federal standard and local equilibrium outcomes. Regarding the uniform standard as given, the representative worker first sets a capital tax rate in each jurisdiction. Then, subject to this local outcomes, the federal authority chooses a level of environmental standard to maximize local workers' welfare. That is, this two-stage problem endogenously determines the uniform environmental standard in the model.

Now, a representative worker as a median voter in each jurisdiction j chooses a time path of capital tax rate to optimize his life-time utility (9), subject to the flow budget constraint (11), the accumulation of mobile capital (8), and the federal uniform environmental standard (31), given an amount of capital stock $K(0)$ in his jurisdiction at the beginning of the time. Therefore, this maximization problem reads the current-value Hamiltonian:

$$H_w(\tau_j, K_j, \mu_j) = U(((1-\alpha)A + \tau_j - \zeta)K_j, \zeta^{-\chi})$$

[20] Cumberland (1979, 1981) suggests the uniformly minimum environmental standards.

$$+\mu_j\left(\left(\frac{1}{\varepsilon}\right)(\alpha A-\tau_j-\rho)K_j+\phi(\alpha A-\tau_j-r_f)\psi(K_j,\ K_j)\right). \quad (32)$$

Appendix B.1 derives as local outcomes the growth rate, the capital tax rate, and the consumption-capital ratio under a given abatement-capital ratio ζ. Thus,

$$\gamma(\zeta)=\left[A-\rho-\frac{\varepsilon\delta-(1-\sigma)(A-\varrho)+\zeta(\varepsilon\phi+1)}{\varepsilon\phi+\sigma}\right]/\varepsilon, \quad (33)$$

$$\tau(\zeta)=-(1-\alpha)A+\frac{\varepsilon\delta-(1-\sigma)(A-\rho)+\zeta(\varepsilon\phi+1)}{\varepsilon\phi+\sigma}, \quad (34)$$

$$c_w(\zeta)=\frac{\varepsilon\delta-(1-\sigma)(A-\rho-\zeta)}{\varepsilon\phi+\sigma}>0. \quad (35)$$

The federal authority then chooses an abatement-capital ratio ζ to maximize the integrated life-time utility (29) subject to local outcomes in eqs. (33), (34), and (35). Appendix B.1 derives the first-order condition with respect to ζ as

$$\frac{dW}{d\zeta}=\frac{(W(1-\sigma)+1/\delta)\kappa}{\varepsilon\delta-(1-\sigma)(A-\rho-\zeta)}\cdot\left(\frac{\chi\eta\bar{c}_w}{\zeta}-1\right)=0, \quad (36)$$

where $W(1-\sigma)+1/\delta=K(0)^{1-\sigma}c_w^{1-\sigma}P^{-\eta(1-\sigma)}/(\delta-\gamma(1-\sigma))$ is a positive term. Since the left multiplier is positive in eq. (36), the optimal uniform standard ζ^* of environmental quality is given as

$$\zeta^*=\chi\eta\bar{c}_w. \quad (\textit{public abatement}) \quad (37)$$

which is not related to a positive capital mobility ϕ. Plugging eq. (37) into eqs. (33), (34), and (35) gives the equilibrium local outcomes

$$\gamma(\zeta^*)=\frac{A-\rho-\bar{c}_w(\Delta_\phi(\sigma)+\chi\eta)}{\varepsilon}, \quad (\textit{growth rate}) \quad (38)$$

$$\tau(\zeta^*)=-(1-\alpha)A+\bar{c}_w(\Delta_\phi(\sigma)+\chi\eta), \quad (\textit{capital tax rate}) \quad (39)$$

$$c_w(\zeta^*)=\bar{c}_w\Delta_\phi(\sigma), \quad (\textit{consumption}) \quad (40)$$

where the superscript * indicates that the uniform standard is at the optimal level. To examine how this optimal uniform standard changes the residents' welfare, the substitution of eqs. (37), (38), and (40) into eq. (29) evaluates the integrated utility as

$$W(\zeta^*)=\begin{cases}\frac{1}{1-\sigma}\left[\left((1-\sigma)\overline{W}+\frac{1}{\delta}\right)\Delta_\phi(1)\Delta_\phi(\sigma)^{-\sigma}-\frac{1}{\delta}\right] & \text{for } 0<\sigma<1,\ \sigma>1\\ \frac{1}{\delta}[\delta\overline{W}+\ln\Delta_\phi(1)-\Delta_\phi(1)+1] & \text{for } \sigma=1\end{cases} \quad (\textit{welfare}) \quad (41)$$

at the optimal level of environmental standard. Thus,

Proposition 3 (uniform environmental standard). *Suppose that the mobility of capital stock is* *positive*, $\phi \in (0, \infty)$. *Then each local jurisdiction has* (i) *a lower growth rate* $\gamma(\zeta^*)$, (ii) *a higher abatement-capital ratio* ζ^* *that is independent of* ϕ *and* (iii) *a higher capital tax rate* $\tau(\zeta^*)$ *under the optimal uniform environmental standard* ζ^* *than under no federal intervention. The federal uniform standard improves* (iv) *the local residents' welfare* $W(\zeta^*)$ *better. If the mobility of capital stock is zero*, $\phi=0$, *then all the local outcomes and welfare level under the optimal uniform environmental standard are the same as under no federal intervention.*

Proof. See Appendix A. □

Eq. (37) states that the optimal uniform environmental standard is independent of any capital mobility $\phi \in [0, \infty)$. The intuition behind this is the following. As the capital mobility increases, the capital tax rate decreases, causing the reduction in public abatement ratio and welfare under no federal intervention. In this case, if it is set to the same as at zero capital mobility, then the public abatement ratio cannot reduce even though the capital tax rate still decreases, which enhances welfare. Thus, the optimal public abatement ratio ζ^* must be independent of capital mobility. The optimal uniform standard preserves the regional environments at the same level as the stock of capital is perfectly immobile ($\phi=0$). Given a level of capital mobility, the consumption growth rate is relatively lower in eq. (38). However, the welfare of local residents is improved under the uniform environmental standard, since the standard saves local environments from degradation by a higher mobility of capital stock (i.e. severe competition).

2. Requirement of lump sum transfer (or tax)

Section 3 observes a reduction in the consumption level of local residents relatively to the amount of capital invested in a jurisdiction, if the capital mobility increases. In this case, the federal government may imposes a requirement of lump sum transfer (or tax) in a redistributive objective. Then local jurisdictions should use the capital tax as a second best, to finance their public abatement activities. According to the local public finance literature, the local environment as a public good might be under-provided in this case.[21] This subsection investigates how the federal restriction on lump sum transfer (or tax) provides the regional environment in this context. The federation is assumed to require a fixed ratio of lump sum transfer to localities at the beginning of the time. This federal requirement can then be defined by the lump sum transfer relative to capital:

$$\xi := \frac{T_j}{K_j}. \tag{42}$$

To derive the optimal requirement of lump sum transfer, backward induction is utilized again in the same way as in the previous subsection. Instead of eq. (11), the budget constraint of workers then becomes

$$C_{wj} = ((1-\alpha)A + \xi)K_j. \tag{43}$$

A representative worker (as a median voter) maximizes his life-time welfare (9) subject to the above budget constraint (43), and the accumulation of capital stock in eq. (8) by choosing a

[21] See this result in Oates and Schwab (1988).

time path of capital tax rate, given $K(0)$ as an initial capital amount in the jurisdiction. The current-value Hamiltonian for this optimization is

$$H_w(\tau_j, K_j, \mu_j)=U(((1-\alpha)A+\xi)K_j, (\tau_j-\xi)^{-\chi}) \\ +\mu_j((1/\varepsilon)(\alpha A-\tau_j-\rho)K_j+\phi(\alpha A-\tau_j-r_f)\psi(K_j, K_f)). \quad (44)$$

Appendix B.2 derives as regional outcomes the growth rate, capital tax rate, and abatement-capital ratio

$$\gamma(\xi)=\left[A-\varrho-\frac{\chi\eta(\varepsilon\delta-(1-\sigma)(\alpha A-\rho))-\xi(1+\varepsilon\phi)}{\varepsilon\phi+\iota}\right]/\varepsilon, \quad (45)$$

$$\tau(\xi)=\frac{\chi\eta(\varepsilon\delta-(1-\sigma)(\alpha A-\rho))+\xi(1+\varepsilon\phi)}{\varepsilon\phi+\iota}, \quad (46)$$

$$g(\xi)=\frac{\chi\eta(\varepsilon\delta-(1-\sigma)(\alpha A-\rho-\xi))}{\varepsilon\phi+\iota}>0, \quad (47)$$

which optimally adjust to any federal transfer requirement ξ. Then the federation chooses ξ to optimize the integrated life-time utility (29) subject to regional outcomes in eqs. (45), (46), and (47). Appendix B.2 derives the first-order condition with respect to the consumption-capital ratio ξ:

$$\frac{\mathrm{d}W}{\mathrm{d}\xi}=\frac{(W(1-\sigma)+1/\delta)\kappa}{\varepsilon\delta-(1-\sigma)(\alpha A-\rho-\xi)}\cdot\left(\frac{\bar{c}_w}{(1-\alpha)A+\xi}-1\right)=0. \quad (48)$$

Note that the left multiplier is positive in eq. (48). Thus, the optimal federal requirement ξ^* of lump sum transfer is given as

$$\xi^*=-(1-\alpha)A+\bar{c}_w \quad (49)$$

which, in turn, leads to the consumption-capital ratio

$$c_w(\xi^*)=\bar{c}_w \quad (\textit{consumption}) \quad (50)$$

by the budget constraint in eq. (43). The optimal consumption-capital ratio $c_w(\xi^*)$ does not depend on any positive capital mobility ϕ. Substituting eq. (49) into the local outcomes in eqs. (45), (46), and (47) yields equilibrium local outcomes

$$\gamma(\xi^*)=\frac{A-\rho-\bar{c}_w(1+\chi\eta\Delta_\phi(\iota))}{\varepsilon}, \quad (\textit{growth rate}) \quad (51)$$

$$\tau(\xi^*)=-(1-\alpha)A+\bar{c}_w(1+\chi\eta\Delta_\phi(\iota)), \quad (\textit{capital tax rate}) \quad (52)$$

$$g(\xi^*)=\chi\eta\bar{c}_w\Delta_\phi(\iota), \quad (\textit{public abatement}) \quad (53)$$

where $\iota:=1-\chi\eta(1-\sigma)$. To investigate how the optimal federal requirement ξ^* alters the residents' welfare, the substitution of eqs. (50), (51), and (53) into eq. (29) evaluates the integrated utility as

$$W(\xi^*)=\begin{cases}\dfrac{1}{1-\sigma}\left[\left((1-\sigma)\overline{W}+\dfrac{1}{\delta}\right)\Delta_\phi(1)\Delta_\phi(\iota)^{-\iota}-\dfrac{1}{\delta}\right] & \text{for } 0<\sigma<1,\ \sigma>1\\ \dfrac{1}{\delta}[\delta\overline{W}+\chi\eta(\ln\Delta_\phi(1)-\Delta_\phi(1)+1)] & \text{for } \sigma=1\end{cases}\quad (welfare)\quad (54)$$

at the optimal level of federal requirement ξ^*. Hence,

Proposition 4 (requirement of lump sum transfer). *Suppose that the mobility of capital stock is positive,* $\phi\in(0,\infty)$. *Then each local jurisdiction has* (i) *a lower growth rate* $\gamma(\xi^*)$, (ii) *a higher, equal, or lower abatement-capital ratio* $g(\xi^*)$ *for* $\sigma<1$, $\sigma=1$, *or* $\sigma>1$ *and* (iii) *a higher capital tax rate* $\tau(\xi^*)$ *under the optimal requirement of lump sum transfer* ξ^* *than under no federal intervention. The federal requirement improves* (iv) *the local residents' welfare* $W(\xi^*)$ *better. If the mobility of capital stock is zero,* $\phi=0$, *then all the local outcomes and welfare level under the optimal requirement of lump sum transfer are the same as under no federal intervention.*

Proof. See Appendix A. □

Eq. (50) implies that the consumption relative to stock of capital is independent of any capital mobility $\phi\in(0,\infty)$. The optimal requirement keeps the consumption-capital ratio in the same level as the capital stock is perfectly immobile ($\phi=0$). The consumption growth rate is relatively lower in eq. (51), since the federal requirement of lump sum transfer (or tax) enforces the local jurisdictions to tax on mobile capital. The regional environment is more degraded for $\phi\in(0,\infty)$, if the elasticity of intertemporal substitution is less than one ($\sigma>1$). In contrast to this prediction as in static models with interjurisdictional competition, we have the opposite result as well, if the elasticity of intertemporal substitution is greater than one ($\sigma<1$). That is, the regional environment as public good is over-provided even with the federal restriction on lump sum transfer (or tax). The local residents' welfare is enhanced under the requirement of lump sum transfer (or tax), since the requirement achieves the redistributive object against the increasing capital mobility (i.e. severe competition).

To complete welfare comparison among three different policy systems, I examine welfare difference between under uniform standard of environmental quality and requirement of lump sum transfer (or tax).

Corollary 1. *Suppose that the mobility of capital stock is positive,* $\phi\in(0,\infty)$. *Then the optimal requirement of lump sum transfer* ξ^* *makes the residents' welfare* $W(\xi^*)$ *better for* $\chi\eta<1$, *equal for* $\chi\eta=1$, *or worse for* $\chi\eta>1$ *than the optimal uniform environmental standard* ζ^*. *If the mobility of capital stock is zero,* $\phi=0$, *then the welfare level under the optimal requirement of lump sum transfer is the same as under the optimal uniform standard of environmental quality.*

Proof. See Appendix A. □

Using Propositions 3 and 4 and Corollary 1, Table 1 summarizes welfare comparison among three alternative policy structures. When the capital mobility is zero ($\phi=0$), the residents in each jurisdiction have the same level of welfare among all three policy systems ($W=W(\zeta^*)=W(\xi^*)=\overline{W}$). In this case, any federal intervention has no effect on the residents' welfare, since the capital stock is perfectly immobile across jurisdictions and thus accumulates only within each jurisdiction's boundary. When the capital mobility is positive ($\phi>0$), either one of two federal interventions enhances the welfare level, however, preventing each

TABLE 1. WELFARE COMPARISON AMONG THREE ALTERNATIVE POLICY STRUCTURES

	$\chi\eta<1$	$\chi\eta=1$	$\chi\eta>1$
$\phi=0$	$W=W(\zeta^*)=W(\xi^*)$	$W=W(\zeta^*)=W(\xi^*)$	$W=W(\zeta^*)=W(\xi^*)$
$\phi>0$	$W<W(\zeta^*)<W(\xi^*)$	$W<W(\zeta^*)=W(\xi^*)$	$W<W(\xi^*)<W(\zeta^*)$

Note: ϕ denotes the degree of capital mobility, η the weight for pollution, and χ the positive elasticity of pollution with respect to the capital-abatement ratio. Also, W denotes welfare with full set of local policies, $W(\zeta^*)$ welfare under a uniform environmental standard, and $W(\xi^*)$ welfare under a federal requirement of revenue transfer.

jurisdiction from competing against the others for the mobile stock of capital across jurisdictions. Note that $\chi\eta$ implies the weight for public abatement ratio in the instantaneous utility function of worker in eq. (10).[22] If $\chi\eta=1$, both of the interventions are equally effective. This is because consumption and public abatement are equally weighted in the worker's utility function. If $\chi\eta>1$, the uniform environmental standards should be preferred to the requirement of lump sum transfer (or tax), since public abatement ratio is more weighted than consumption. This is the case where the residents' environmental concern is relatively higher or the regional environment is relatively more polluted by the capital stock induced in the jurisdiction. On the other case ($\chi\eta<1$), the lump sum transfer (or tax) requirement is more effective than the uniform standard, because consumption is more weighted than public abatement ratio. Since the increased capital mobility transfers the burden of pollution abatement to each jurisdiction, the federal intervention is necessary to save the jurisdictions.

V. *Conclusion*

The paper identifies that an increase in capital mobility provides local jurisdictions with a higher growth rate. Since the increasing mobility of capital strengthens the jurisdictions to set a lower capital tax rate, the stock of capital can rapidly accumulate in the jurisdictions. Although it has a positive effect on the growth rate, the increase in capital mobility degrades regional environments. This finding supports the hypothesis of "race to the bottom" in environmental standards. Thus, the capital mobility presents a trade-off between growth rate and environmental quality. If the stock of capital is relatively more mobile, each jurisdiction cannot avoid to collect relatively less revenue from capital stock. To finance the local public expenditure on pollution abatement, the jurisdiction relies relatively more on the lump sum tax (or relatively less on the lump sum transfer). That is, each jurisdiction "imports tax" within its regional boundary. The increasing capital mobility transfers the burden of public funds from capitalists to local residents. Therefore, both of the federal interventions are meaningful and could perform

[22] If eq. (1) is plugged into eq. (10), then the instantaneous utility function of worker becomes

$$U(C_{wj}, P_j)=U(G_{wj}, G_j/K_j)=\begin{cases} \dfrac{(C_{wj}\,(G_j/K_j)^{\chi\eta})^{1-\sigma}-1}{1-\sigma} & \text{for } 0<\sigma<1,\ \sigma>1 \\ \ln C_{wj}+\chi\eta\ln\,(G_j/K_j) & \text{for } \sigma=1 \end{cases}$$

where $\chi\eta$ is the weight for public abatement ratio.

key roles in reality.

I do not consider the jurisdictions where the workers as actual residents are heterogenous as in Oates and Schwab (1988). The impact of increasing capital mobility would be different according to alternative outcome from majority voting. To investigate this, one can easily extend this model, however. A majority of non-wage workers could be an alternative against the increasing mobility of capital. This outcome might reduce the negative effects on regional environments and welfare, since the non-wage workers depend relatively less on the amount of capital induced in the jurisdiction. But, the impact of increasing capital mobility is somewhat negative in the majority of wage workers. The income source of wage workers is very related to the level of capital stock. Thus the wage workers would vote for even lower capital tax rates as the stock of capital gets more mobile.

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A Proofs

Proof of Lemma 1. (i). Assume that eq. (28) are satisfied. Then $A-\rho>\varepsilon(1+\chi\eta)\delta>0$. The parameter κ is positive for $\sigma\geq 1$. If $\sigma<1$, then

$$\kappa=1-(1+\chi\eta)(1-\sigma)=1-\frac{\varepsilon(1+\chi\eta)\delta}{A-\rho}\cdot\frac{(A-\rho)(1-\sigma)}{\varepsilon\delta}>0,$$

since $0<\varepsilon\delta(1+\chi\eta)/(A-\rho)<1$ and $0<(A-\rho)(1-\sigma)/\varepsilon\delta<1$ from rearranging eq. (28).
(ii). The growth rate is positive for arbitrary $\phi\in[0,\infty)$:

$$\gamma=\frac{A-\rho-(1+\chi\eta)\bar{c}_w\Delta_\phi(\kappa)}{\varepsilon}=\frac{\varepsilon(A-\rho)\phi+A-\rho-\varepsilon\delta(1+\chi\eta)}{\varepsilon(\varepsilon\phi+\kappa)}>0,$$

since $A-\rho>0$ and $A-\rho-\varepsilon\delta(1+\chi\eta)>0$ from using (i) and rearranging the first inequality in eq. (28). The transversality condition (19) is satisfied for arbitrary $\phi\in[0,\infty)$ as follows:

$$\lim_{t\to\infty}e^{-\delta t}\mu K=\lim_{t\to\infty}e^{-(\delta-\gamma(1-\sigma))t}\mu(0)K(0)=\lim_{t\to\infty}e^{-(\delta-\gamma(1-\sigma))t}\cdot\frac{U_C(0)\varepsilon K(0)}{\varepsilon\phi+1}=0,$$

since

$$\delta-\gamma(1-\sigma)=c_w(1/\varepsilon+\phi)=\frac{\bar{c}_w\Delta_\phi(\kappa)}{\varepsilon\Delta_\phi(1)}=\frac{\varepsilon\delta-(1-\sigma)(A-\rho)}{\varepsilon\kappa}\cdot\frac{\Delta_\phi(\kappa)}{\Delta_\phi(1)}>0,$$

and the term $U_C(0)\varepsilon K(0)/(\varepsilon\phi+1)$ is positive and finite. □

Proof of Proposition 3. (i). The difference of growth rates between under no federal intervention and under the optimal uniform environmental standard is

$$\begin{aligned}\gamma-\gamma(\zeta^*)&=-\frac{\bar{c}_w[(1+\chi\eta)\Delta_\phi(\kappa)-(\Delta_\phi(\sigma)+\chi\eta)]}{\varepsilon}\\&=\frac{\chi\eta\bar{c}_w}{\kappa\sigma}\cdot\frac{\phi\Delta_\phi(\kappa)\Delta_\phi(\sigma)}{\Delta_\phi(1)}\\&>0\quad\text{if } \phi>0 \text{ and}\\&=0\quad\text{if } \phi=0.\end{aligned}$$

(ii). The difference of abatement-capital ratios between under no federal intervention and under the optimal uniform environmental standard is

$$\begin{aligned}g-\zeta^*&=\chi\eta\bar{c}_w(\Delta_\phi(\kappa)-1)\\&=-\frac{\chi\eta\varepsilon\bar{c}_w}{\kappa}\cdot\phi\Delta_\phi(\kappa)\\&<0\quad\text{if } \phi>0\text{, and}\\&=0\quad\text{if } \varphi=0.\end{aligned}$$

(iii). The difference of capital tax rates between under no federal intervention and under the optimal uniform environmental standard is

$$\begin{aligned}\tau-\tau(\zeta^*)&=\bar{c}_w[(1+\chi\eta)\Delta_\phi(\kappa)-(\Delta_\phi(\sigma)+\chi\eta)]\\&=-\frac{\varepsilon\chi\eta\bar{c}_w}{\kappa\sigma}\cdot\frac{\phi\Delta_\phi(\kappa)\Delta_\phi(\sigma)}{\Delta_\phi(1)}\\&<0\quad\text{if } \phi>0 \text{ and}\\&=0\quad\text{if } \phi=0.\end{aligned}$$

(iv). The difference of welfare between under no federal intervention and under the optimal uniform environmental standard is

$$W-W(\zeta^*)=\begin{cases}\dfrac{(1-\sigma)\overline{W}+1/\delta}{1-\sigma}\cdot\Delta_\phi(1)(\Delta_\phi(\kappa)^{-\kappa}-\Delta_\phi(\sigma)^{-\sigma}) & \text{for } 0<\sigma<1,\ \sigma>1\\ \dfrac{1}{\delta}\chi\eta(\ln\Delta_\phi(1)-\Delta_\phi(1)+1) & \text{for } \sigma=1\end{cases}.$$

a) Suppose that $\sigma<1$ (or $\sigma>1$). Note that $(1-\sigma)\overline{W}+1/\delta>0$ from eq. (30); $\Delta_\phi(1)>0$ from

Definition 1; and $\kappa-\sigma=-\chi\eta(1-\sigma)$. Also note from Definition 1 that $\Delta_\phi(x)^{-x}=\left(\frac{x}{\varepsilon\phi+x}\right)^{-x}=\left[\left(1+\frac{1}{x/\varepsilon\phi}\right)^{x/\varepsilon\phi}\right]^{\varepsilon\phi}$ is strictly increasing in $x\in(0,\infty)$ for $\phi>0$ since $\left(1+\frac{1}{x/\varepsilon\phi}\right)^{x/\varepsilon\phi}$ is well known as a strictly increasing function of $x/\varepsilon\phi$ for a given value $\varepsilon\phi$; and $\Delta_\phi(x)^{-x}=\left(\frac{x}{\varepsilon\phi+x}\right)^{-x}=1$ with any $x\in(0,\infty)$ for $\phi=0$. If $\phi>0$, then $W<W(\zeta^*)$ since $\Delta_\phi(\kappa)^{-\kappa}<\Delta_\phi(\sigma)^{-\sigma}$ with $\kappa<\sigma$ (or $\Delta_\phi(\kappa)^{-\kappa}>\Delta_\phi(\sigma)^{-\sigma}$ with $\kappa>\sigma$). If $\phi=0$, then $W=W(\zeta^*)$ since $\Delta_\phi(\kappa)^{-\kappa}=\Delta_\phi(\sigma)^{-\sigma}=1$.

b) Suppose that $\sigma=1$. Note that $\ln\Delta_\phi(1)-\Delta_\phi(1)+1<0$ for $\phi>0$ since $\ln\Delta_0(1)-\Delta_0(1)+1=0$, and $\frac{d(\ln\Delta_\phi(1)-\Delta_\phi(1)+1)}{d\phi}=-\frac{\varepsilon^2\phi}{(\varepsilon\phi+1)^2}<0$ for $\phi>0$ ($=0$ for $\phi=0$); and $\ln\Delta_\phi(1)-\Delta_\phi(1)+1=0$ for $\phi=0$. If $\phi>0$, then $W<W(\zeta^*)$ since $\ln\Delta_\phi(1)-\Delta_\phi(1)+1<0$. If $\phi=0$, then $W=W(\zeta^*)$ since $\ln\Delta_\phi(1)-\Delta_\phi(1)+1=0$. □

Proof of Proposition 4. First, I prove that the parameter ι is positive. If $\sigma\geq1$, then $\iota=1-\chi\eta(1-\sigma)>0$. Suppose that $\sigma<1$. Since $\kappa=1-(1+\chi\eta)(1-\sigma)>0$ by Lemma 1 and $1-\sigma>0$, we have that $0<(1+\chi\eta)(1-\sigma)<1$. Then $\iota=1-\chi\eta(1-\sigma)=1-(\chi\eta/(1+\chi\eta))(1+\chi\eta)(1-\sigma)>0$. (i). The difference of growth rates between under no federal intervention and under the optimal requirement of lump sum transfer is

$$\begin{aligned}\gamma-\gamma(\xi^*)&=-\frac{\bar{c}_w[(1+\chi\eta)\Delta_\phi(\kappa)-(1+\chi\eta\Delta_\phi(\iota))]}{\varepsilon}\\&=\frac{\bar{c}_w}{\kappa\iota}\cdot\frac{\phi\Delta_\phi(\kappa)\Delta_\phi(\iota)}{\Delta_\phi(1)}\\&>0\quad\text{if }\phi>0\text{, and}\\&=0\quad\text{if }\phi=0.\end{aligned}$$

(ii). The difference of abatement-capital ratios between under no federal intervention and the optimal requirement of lump sum transfer is

$$\begin{aligned}g-g(\xi^*)&=\chi\eta\bar{c}_w(\Delta_\phi(\kappa)-\Delta_\phi(\iota))\\&=-(1-\sigma)\cdot\frac{\chi\eta\bar{c}_w\varepsilon}{\kappa\iota}\cdot\phi\Delta_\phi(\kappa)\Delta_\phi(\iota)\\&<,=,\text{ or }>0\quad\text{for }\sigma<,=,\text{ or }>1\quad\text{when }\phi>0\text{ and}\\&=0\quad\text{when }\phi=0.\end{aligned}$$

(iii). The difference of capital tax rates between under no federal intervention and under the optimal requirement of lump sum transfer is

$$\tau-\tau(\xi^*)=\bar{c}_w[(1+\chi\eta)\Delta_\phi(\kappa)-(1+\chi\eta\Delta_\phi(\iota))]$$

$$= -\frac{\varepsilon \bar{c}_w}{\kappa \iota} \cdot \frac{\phi \Delta_\phi(\kappa) \Delta_\phi(\iota)}{\Delta_\phi(1)}$$

$$< 0 \quad \text{if } \phi > 0, \text{ and}$$

$$= 0 \quad \text{if } \phi = 0.$$

(iv). The difference of welfare levels between under no federal intervention and under the optimal requirement of lump sum transfer is

$$W - W(\xi^*) = \begin{cases} \dfrac{(1-\sigma)\overline{W} + 1/\delta}{1-\sigma} \cdot \Delta_\phi(1)(\Delta_\phi(\kappa)^{-\kappa} - \Delta_\phi(\iota)^{-\iota}) & \text{for } 0<\sigma<1,\ \sigma>1 \\ \dfrac{1}{\delta}(\ln \Delta_\phi(1) - \Delta_\phi(1) + 1) & \text{for } \sigma = 1 \end{cases}.$$

a) Suppose that $\sigma<1$ (or $\sigma>1$). Note that $(1-\sigma)\overline{W}+1/\delta>0$ from eq. (30); $\Delta_\phi(1)>0$ from Definition 1; and $\kappa-\iota=-(1-\sigma)$. Also note from Proof (iv) a) of Proposition 3 that $\Delta_\phi(x)^{-x}$ is strictly increasing in $x\in(0, \infty)$ for $\phi>0$; and $\Delta_\phi(x)^{-x}=1$ with any $x\in(0, \infty)$ for $\phi=0$. If $\phi>0$, then $W<W(\xi^*)$ since $\Delta_\phi(\kappa)^{-\kappa}<\Delta_\phi(\iota)^{-\iota}$ with $\kappa<\iota$ (or $\Delta_\phi(\kappa)^{-\kappa}>\Delta_\phi(\iota)^{-\iota}$ with $\kappa>\iota$). If $\phi=0$, then $W=W(\xi^*)$ since $\Delta_\phi(\kappa)^{-\kappa}=\Delta_\phi(\iota)^{-\iota}=1$.
b) Suppose that $\sigma=1$. Note from Proof (iv) b) of Proposition 3 that $\ln \Delta_\phi(1)-\Delta_\phi(1)+1<0$ for $\phi>0$; and $\ln \Delta_\phi(1)-\Delta_\phi(1)+1=0$ for $\phi=0$. If $\phi>0$, then $W<W(\xi^*)$ since $\ln \Delta_\phi(1)-\Delta_\phi(1)+1<0$. If $\phi=0$, then $W=W(\xi^*)$ since $\ln \Delta_\phi(1)-\Delta_\phi(1)+1=0$. □

Proof of Corollary 1. The difference of welfare levels between under the optimal uniform standard of environmental quality and under the optimal requirement of lump sum transfer is

$$W(\zeta^*) - W(\xi^*) = \begin{cases} \dfrac{(1-\sigma)\overline{W} + 1/\delta}{1-\sigma} \cdot \Delta_\phi(1)(\Delta_\phi(\sigma)^{-\sigma} - \Delta_\phi(\iota)^{-\iota}) & \text{for } 0<\sigma<1,\ \sigma>1 \\ \dfrac{1}{\delta}(1-\chi\eta)(\ln \Delta_\phi(1) - \Delta_\phi(1) + 1) & \text{for } \sigma = 1 \end{cases}.$$

a) Suppose that $\sigma<1$ (or $\sigma>1$). Note that $(1-\sigma)\overline{W}+1/\delta>0$ from eq. (30); $\Delta_\phi(1)>0$ from Definition 1; and $\sigma-\iota=-(1-\chi\eta)(1-\sigma)$. Also note from Proof (iv) a) of Proposition 3 that $\Delta_\phi(x)^{-x}$ is strictly increasing in $x\in(0, \infty)$ for $\phi>0$; and $\Delta_\phi(x)^{-x}=1$ with any $x\in(0, \infty)$ for $\phi=0$. If $\phi>0$, then $W(\zeta^*)<W(\xi^*)$ for $\chi\eta<1$ since $\Delta_\phi(\sigma)^{-\sigma}<\Delta_\phi(\iota)^{-\iota}$ with $\sigma<\iota$ (or $\Delta_\phi(\sigma)^{-\sigma}>\Delta_\phi(\iota)^{-\iota}$ with $\sigma>\iota$); $W(\zeta^*)=W(\xi^*)$ for $\chi\eta=1$ since $\Delta_\phi(\sigma)^{-\sigma}=\Delta_\phi(\iota)^{-\iota}$ with $\sigma=\iota$; and $W(\zeta^*)>W(\xi^*)$ for $\chi\eta>1$ since $\Delta_\phi(\sigma)^{-\sigma}>\Delta_\phi(\iota)^{-\iota}$ with $\sigma>\iota$ (or $\Delta_\phi(\sigma)^{-\sigma}<\Delta_\phi(\iota)^{-\iota}$ with $\sigma<\iota$). If $\phi=0$, then $W(\zeta^*)=W(\xi^*)$ since $\Delta_\phi(\sigma)^{-\sigma}=\Delta_\phi(\iota)^{-\iota}=1$.
b) Suppose that $\sigma=1$. Note from Proof (iv) b) of Proposition 3 that $\ln \Delta_\phi(1)-\Delta_\phi(1)+1<0$ for $\phi>0$; and $\ln \Delta_\phi(1)-\Delta_\phi(1)+1=0$ for $\phi=0$. If $\phi>0$, then $W(\zeta^*)<W(\xi^*)$ for $\chi\eta<1$; $W(\zeta^*)=W(\xi^*)$ for $\chi\eta=1$; and $W(\zeta^*)>W(\xi^*)$ for $\chi\eta>1$ since $\ln \Delta_\phi(1)-\Delta_\phi(1)+1<0$. If $\phi=0$, then $W(\zeta^*)=W(\xi^*)$ since $\ln \Delta_\phi(1)-\Delta_\phi(1)+1=0$. □

B Derivations

B.1 Derivation of optimal uniform environmental standard

Local outcomes for a given uniform standard

Differentiating the current-value Hamiltonian (32) with respect to the capital tax rate τ, the sock of capital K, and the shadow price of capital μ, and then substituting the ex-post equilibrium conditions (13) and (14), we take the following first-order conditions:

$$U_C=\mu(1/\varepsilon+\phi)K, \tag{55}$$

$$((1-\alpha)A+\tau-\zeta)U_C-\mu(\alpha A-\tau-\rho)/\varepsilon=\delta\mu-\dot{\mu}, \tag{56}$$

$$\dot{K}=(1/\varepsilon)(\alpha A-\tau-\rho)K. \tag{57}$$

Differentiating eq. (55) with respect to time, and then replacing this result and eq. (55) into eq. (56), we get

$$\frac{\dot{C}_w}{C_w}=(((1-\alpha)A+\tau-\zeta)(1/\varepsilon+\phi)+(\alpha A-\tau-\rho)/\varepsilon-\delta)/\sigma, \tag{58}$$

which is the Keynes-Ramsey rule that describes the optimal saving-investment path for the capital stock under a uniform standard.

The optimal uniform standard

The total differentiation of the integrated life-time utility function (29) gives

$$\mathrm{d}W=(W(1-\sigma)+1/\delta)\left(\frac{\mathrm{d}c_w}{c_w}-\eta\frac{\mathrm{d}P}{P}+\frac{\mathrm{d}\gamma}{\delta-\gamma(1-\sigma)}\right). \tag{59}$$

Differentiating totally the growth rate $\gamma(\zeta)$ in eq. (33), the consumption-capital ratio $c_w(\zeta)$ in eq. (35), and the pollution function (1), we have

$$\frac{\mathrm{d}\gamma}{\delta-\gamma(1-\sigma)}=-\frac{(1/\varepsilon)\mathrm{d}\zeta}{\delta-(1-\sigma)(A-\rho)/\varepsilon+\zeta(1-\sigma)/\varepsilon}. \tag{60}$$

$$\frac{\mathrm{d}c_w}{c_w}=\frac{(1/\varepsilon)(1-\sigma)\mathrm{d}\zeta}{\delta-(1-\sigma)(A-\rho)/\varepsilon+\zeta(1-\sigma)/\varepsilon}, \tag{61}$$

$$\frac{\mathrm{d}P}{P}=-\chi\frac{\mathrm{d}\zeta}{\zeta}. \tag{62}$$

By plugging eqs. (60), (61), and (62) into eq. (59), we arrive at the first-order condition (36) for the uniform standard ζ of environmental quality.

B.2 Derivation of optimal requirement of lump sum transfer (or tax)

Local outcomes for a given requirement

Differentiating the current-value Hamiltonian (44) with respect to the capital tax rate τ, the capital stock K, and the shadow price of capital μ, and then replacing the ex-post equilibrium conditions in eqs. (13) and (14), we get the first-order conditions as

$$U_P = -\mu(1/\varepsilon + \phi)K\chi(\tau - \xi)^{\chi+1}, \tag{63}$$

$$((1-\alpha)A + \xi)U_C + \mu(\alpha A - \tau - \rho)/\varepsilon = \delta\mu - \dot{\mu}, \tag{64}$$

$$\dot{K} = (1/\varepsilon)(\alpha A - \tau - \rho)K. \tag{65}$$

Differentiating eq. (63) with respect to time and plugging the derivative and eq. (63) into eq. (64) yield

$$\frac{\dot{C}_w}{C_w} = -\left(\frac{(1/\varepsilon + \varphi)(\tau - \xi)}{\chi\eta} - \delta - (\eta(1-\sigma)+1)\frac{\dot{P}}{P}\right)/(1-\sigma), \tag{66}$$

which is the Keynes-Ramsey rule that implies the optimal saving-investment path for the stock of capital under a federal requirement of transfer.

The optimal requirement

Differentiating totally the consumption-capital ratio $c_w(\xi)$ in eq. (43), the growth rate $\gamma(\xi)$ in eq. (45), the abatement-capital ratio $g(\xi)$ in eq. (47), and the pollution function (1), we have

$$\frac{\mathrm{d}c_w}{c_w} = \frac{\mathrm{d}\xi}{(1-\alpha)A + \xi}, \tag{67}$$

$$\frac{\mathrm{d}\gamma}{\delta - \gamma(1-\sigma)} = -\frac{\mathrm{d}g}{g(1-\sigma)}, \tag{68}$$

$$\frac{\mathrm{d}g}{g} = \frac{(1-\sigma)(1/\varepsilon)\mathrm{d}\xi}{\delta - (1-\sigma)(1/\varepsilon)(\alpha A - \rho - \xi)}, \tag{69}$$

$$\frac{\mathrm{d}P}{P} = -\chi\frac{\mathrm{d}g}{g}. \tag{70}$$

Hence, we arrive at eq. (48) by substituting eq. (69) into eqs. (68) and (70), and then plugging two results and eq. (67) into eq. (59).