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Intergenerational Transfers, Lifetime Welfare and Resource Preservation

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Abstract

This paper analyzes overlapping-generations models where natural capital is owned by selfish agents. Transfers in favor of young agents reduce the rate of depletion and increase output growth. It is shown that intergenerational transfers may be preferred to laissez-faire by an indefinite sequence of generations: if the resource share in production is sufficiently high, the welfare gain induced by preservation compensates for the loss due to taxation. This conclusion is reinforced when other assets are available, e.g. man-made capital, claims on monopoly rents, and R&D investment. Transfers raise the welfare of all generations, except that of the first resource owner: if resource endowments are taxed at time zero, all successive generations support resource-saving policies for purely selfish reasons.

Keywords Distortionary Taxation, Intergenerational Transfers, Overlapping Generations, Renewable Resources, Sustainability, Technological Change.

JEL Codes H30, Q01, Q20

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1 Introduction

Preserving intergenerational equity has become a worldwide political concern, and achieving sustainability is increasingly considered a relevant social goal. A major source of intergenerational conflict is represented by the intensive use of natural resources in the production process, since over-exploitation represents a threat for the ability of future generations to meet their own needs. Since Hotelling's (1931) seminal work, economists have pointed out several potential sources of the problem: over-exploitation may result from market incompleteness, excessive competition, myopic behavior, and the lack of incentives for investment in preservation. Accordingly, public intervention may be called for either to restore efficiency (Toman, 1987) or sette conflicts between intertemporal efficiency and intergenerational fairness (Howarth and Norgaard, 1990).[1]

In recent times, the attribution of property rights over natural resources has gained much attention in the policy debate. However, neither sustainability nor resource preservation are guaranteed when natural capital is private property. This result holds in general equilibrium models with infinitely-lived agents (Pezzey, 1992), and is furthermore valid when assuming selfish agents with finite lifetimes (Mourmouras, 1993): market valuation of resource assets can only limit the depletion rate to the extent that preserving natural capital is profitable to agents currently alive. Consequently, achieving intergenerational fairness requires a system of transfers that redistributes income among generations: examples in the recent literature on resource economics include Howarth (1991), Mourmouras (1993), Krautkraemer and Batina (1999), Gerlagh and Keyzer (2001). The logic underlying these contributions is that of pursuing intergenerational fairness while preserving intertemporal efficiency, and this typically implies considering lump-sum transfers. However, the welfare effects of transfers can also be investigated from a different perspective, which is alternative to (but not conflicting with) the efficiency-and-equity logic. Real-world policymaking is often constrained by institutional feasibility: lump-sum taxes have a limited application, and policies involving intergenerational transfers likely need the support of the constituency. Building on this point, this paper poses the following question. Consider an economy with overlapping generations where natural capital is essential for production. Suppose that, under laissez-faire conditions, lifetime utility of future generations will be lower than current welfare levels. Would *selfish* agents agree on a system of intergenerational transfers implying a lower rate of resource depletion?

Postulating a direct link between political support and individual welfare, this paper tackles the issue by characterizing individual payoffs in a regime-contingent fashion - that is, lifetime utility levels of a given generation under alternative policy regimes - assuming that transfers are implemented through distortionary measures. The crucial result is that a higher degree of resource preservation may be strictly preferred by private agents, provided that a critical condition on technological parameters is satisfied. More precisely, it is shown that if the resource-share in production is sufficiently high, taxing natural capital incomes to subsidize young generations guarantees higher lifetime utility for all newborn generations. The reason for this result is that a lower rate of depletion increases the growth rate of the economy in the subsequent period: if

[1] Bromley (1990) forcefully argues that environmental policy should not be restricted to efficiency targets. In line with this view is the idea that sustainability is a matter of intergenerational equity and, once the social objective incorporates fairness concerns, efficiency *per se* does not guarantee socially optimal outcomes (Howarth and Norgaard, 1990).

resource productivity is sufficiently high, this positive effect on second-period income more than compensates the negative effect of taxation, and agents will prefer non-zero transfers to laissez-faire conditions for purely selfish reasons. Moreover, this mechanism is enhanced by the presence of other assets representing individual wealth. Extending the model to include man-made capital, monopoly rents and R&D sectors, it is shown that the critical condition becomes less restrictive because the returns from these assets also benefit from the positive growth effect induced by a higher degree of preservation.

From a policymaking perspective, the private desire for resource-saving policies unfolds if young generations are credibly pre-committed. In this regard, it is shown that permanent transfers may arise as an indefinite sequence of lifetime contracts: if young agents were asked to choose between permanent transfers and permanent laissez-faire, the former option would be preferred. In the absence of commitment devices, transfers may arise as political equilibria in sequential voting games when young agents have majority power or old agents are induced to cooperate by the presence of regime-switching costs. In all the above cases, the intergenerational distribution of benefits under resource-saving policies is not Pareto comparable with that obtained under laissez-faire, since resource owners at time zero bear the burden of initial taxation: similarly to Gale (1973), if the first resource owner partially renounces to his claim over initial endowments, the transmission of this credit forward in time yields welfare gains for all successive generations.

2 The basic model

In line with recent literature, a *sustainable path* is defined as a path along which welfare is non-declining over time. The economy has an overlapping-generations structure: each agent lives for two periods, and enjoys utility from consumption when young (c) and consumption when old (e). Population in period t consists of N_t young and N_{t-1} old individuals, with a constant rate n of population growth: $N_{t+1} = N_t(1+n)$. Denoting by U_t the lifetime utility of an agent born in period t, sustainability requires

$$U_{t+1}(c_{t+1}, e_{t+2}) \geq U_t(c_t, e_{t+1}), \quad \forall t \in [0, \infty). \tag{1}$$

Denoting by R_t the stock of natural resources available in the economy, we also define *no depletion paths* as those paths satisfying

$$R_{t+1} \geq R_t, \quad \forall t \in [0, \infty). \tag{2}$$

Our formal analysis draws on Mourmouras (1993) and Krautkraemer and Batina (1999): in this section, we augment the Mourmouras (1993) model by considering exogenous technical progress; further extensions regarding man-made capital, monopoly rents and endogenous technical change are developed later in section 4.

Prospects for sustainability and natural preservation depend on the intergenerational distribution of entitlements, which affects the time-path of resource use, and in turn, the production frontier and consumption possibilities of generations yet to be born. In this regard, we assume a grandfathering process *à la* Krautkraemer and Batina (1999): at the beginning of period t, the whole stock of natural resources in the economy R_t is held by old agents. Part of R is used as *natural capital* in production (X), while the remaining stock constitutes *resource assets* (A):

$$R_t = A_t + X_t. \tag{3}$$

Old agents sell resource assets A_t to young agents at unit price q_t, and receive a gross marginal rent p_t for each unit of natural capital X_t supplied to firms. Quantities of resource assets and natural capital per young individual are denoted by $a_t = A_t/N_t$ and $x_t = X_t/N_t$, respectively. While natural capital is destroyed in the production process, resource assets sold to newborn generations are brought forward in time: in each period, the resource grows at constant regeneration rate ε, implying

$$R_{t+1} = (1+\varepsilon)(R_t - X_t) = (1+\varepsilon) A_t. \tag{4}$$

Only young agents work, supplying one unit of labor services. The consumption good is produced by means of natural capital and labor, according to technology

$$\begin{aligned} Y_t &= (m_t X_t)^{\alpha} (N_t)^{1-\alpha}, \quad &(5) \\ m_t &= m_{t-1}(1+\delta), \quad &(6) \end{aligned}$$

where Y_t is aggregate output, N_t equals total labor units supplied by the currently young, and m_t is the state of technology, representing a process that enhances the productivity of natural capital in each period: $\delta > 0$ is the rate of *resource-augmenting* technological progress.[2] Denoting by w the wage rate, profit maximization implies

$$\begin{aligned} p_t &= \alpha y_t x_t^{-1} = \alpha m_t^{\alpha} x_t^{\alpha-1}, \quad &(7) \\ w_t &= (1-\alpha) y_t = (1-\alpha) m_t^{\alpha} x_t^{\alpha}, \quad &(8) \end{aligned}$$

where $y = Y/N$ is output per worker.

Intergenerational transfers take the following form: young agents' investment is subsidized by taxing the income from natural capital of old agents, and fiscal authorities keep a balanced budget in each period. Formally,

$$\begin{aligned} c_t &= w_t - q_t (1-d_t) a_t, \quad &(9) \\ e_{t+1} &= [p_{t+1}(1-\tau_{t+1}) x_{t+1} + q_{t+1} a_{t+1}](1+n), \quad &(10) \\ p_t \tau_t X_t &= q_t d_t A_t, \quad &(11) \\ y_t &= c_t + e_t (1+n)^{-1}. \quad &(12) \end{aligned}$$

Equations (9) and (10) represent budget constraints faced by each individual born in period t, where d is the subsidy rate on investment in resource assets, and τ is the tax rate on natural capital income. Equation (11) is the government budget constraint, and equation (12) is the aggregate constraint of the economy. Agents are homogeneous and have logarithmic preferences: lifetime utility is $U_t = \log c_t + \beta \log e_{t+1}$, where $\beta \in (0,1)$ is the individual discount factor. Equilibrium in the resource market requires

$$q_t = p_t (1-\tau_t) \tag{13}$$

in each period. The consumer problem consists of choosing c_t and e_{t+1} in order to maximize lifetime utility subject to (9)-(10): first order conditions read

$$\frac{e_{t+1}}{\beta c_t} = \frac{q_{t+1}(1+\varepsilon)}{q_t(1-d_t)}. \tag{14}$$

[2] In general, technical progress in Cobb-Douglas technologies is input neutral, and (5) may be rewritten as $Y = X^{\alpha} L^{1-\alpha} \hat{m}$, where the growth rate of $\hat{m} = m^{\alpha}$ is the Hicks-neutral rate of technical progress. Specification (5) is chosen to emphasize that prospects for sustainability depend on the resource-saving effect of technical progress (δ), and not on its global effect of on output levels ($\hat{m}_{t+1}/\hat{m}_t$) - see Proposition 1; cf. Valente (2005).

The temporary equilibrium of the economy is characterized by the following relations (see Appendix): the *natural capital-resource asset ratio* (z) equals

$$z_t \equiv \frac{x_t}{a_t} = \frac{\alpha (1+\beta)}{\beta (1-\alpha)} (1-\tau_t)(1-d_t), \tag{15}$$

and the dynamics of the economy are described by[3]

$$\theta^R_{t+1} = \frac{1+\varepsilon}{1+z_t}, \tag{16}$$

$$\theta^x_{t+1} = \frac{z_{t+1}(1+\varepsilon)}{z_t(1+z_{t+1})(1+n)}, \tag{17}$$

$$\theta^y_{t+1} = \left[\frac{z_{t+1}(1+\rho)}{z_t(1+z_{t+1})}\right]^\alpha, \tag{18}$$

where $\theta^v_{t+1} = (v_{t+1}/v_t)$ for the generic variable v_t. Note that in equation (18) we have defined the *augmentation rate* ρ as

$$1+\rho = (1+\varepsilon)(1+\delta)(1+n)^{-1}. \tag{19}$$

In the following subsections we describe the laissez-faire equilibrium, and analyze the implications of intergenerational transfers.

2.1 The laissez-faire economy

Setting tax-subsidy rates equal to zero, it follows from (15) that the natural capital-resource asset ratio is constant over time:

$$z_t = \frac{\alpha (1+\beta)}{\beta (1-\alpha)} = \tilde{z} \text{ for all } t. \tag{20}$$

The laissez-faire economy exhibits the knife-edge property: setting $z_{t+1} = z_t = \tilde{z}$ in (18), the net growth rate of output per worker is constant over time, and it can be positive, negative, or equal to zero, depending on parameters. With respect to Mourmouras (1993), the presence of technological progress crucially modifies the link between resource depletion and sustainability, determining possible conflicts among alternative social objectives. In fact, a necessary and sufficient condition for no depletion in the laissez-faire economy is[4]

$$\tilde{z} \leq \varepsilon, \tag{21}$$

whereas

Proposition 1 *A necessary and sufficient condition for sustainability in the laissez-faire economy is*

$$\tilde{z} \leq \rho, \tag{22}$$

or equivalently

$$1+\gamma \leq \left(\frac{1-\alpha}{\alpha}\right)\left[\frac{(1+\delta)(1+\varepsilon)}{(1+n)} - 1\right] - 1, \tag{23}$$

where $\gamma = \beta^{-1} - 1$ is the individual pure rate of time preference.

[3] Substituting (15) in (3) and (4) yields (16) and (17). From (5) and (6), $y = m^\alpha x^\alpha$ so that $\theta^y = [(1+\delta)\theta^x]^\alpha$, which implies (18) by (17).

[4] From (16), no depletion (*i.e.* $\theta^R \geq 1$) requires that (21) be satisfied.

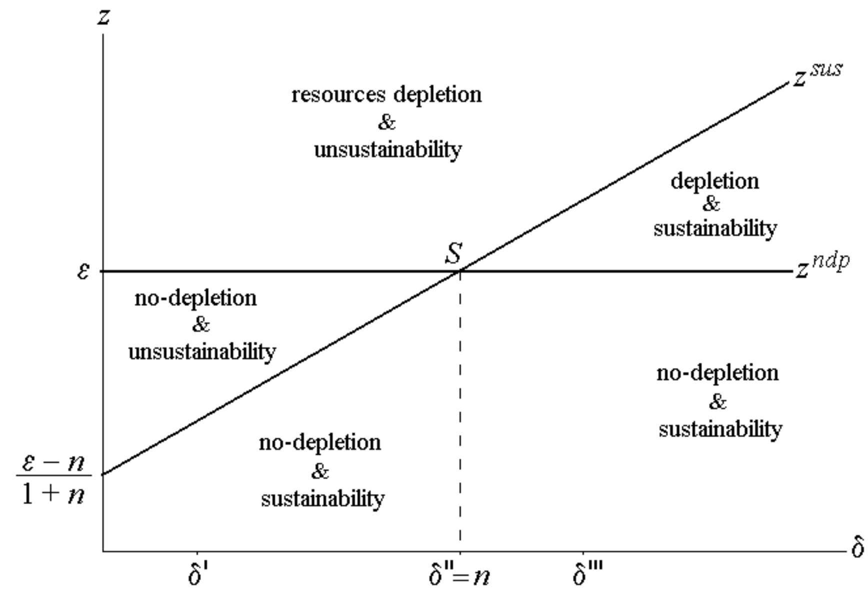

Figure 1: The basic model. From (21) and (22), the sustainability threshold $z^{sus} = \rho$ increases with δ, while the no depletion locus $z^{ndp} = \varepsilon$ is horizontal in the $(\delta,\ z)$ plane. if $\delta < n$, the laissez-faire economy may exhibit no depletion together with unsustainability; if $\delta > n$, the economy may exhibit resource depletion together with sustainability.

Expression (23) is conceptually analogous to the long-run sustainability condition which holds in economies with infinitely-lived agents: in the standard capital-resource model, optimal consumption per capita is asymptotically non-decreasing if the social discount rate does not exceed the sum of the rates of technical progress and natural regeneration (Valente, 2005). Similarly, (23) shows that sustainability obtains provided that the joint effect of δ and ε is not offset by the impatience to consume (γ).

Whether sustainability conditions are more restrictive than conditions for no depletion depends on the rates of technological progress and population growth: no depletion per se does not guarantee sustained utility, and different combinations of parameters may determine sustainability, no depletion, both, or none of the two. The interrelations, and possible conflicts, between alternative social objectives are described in Figure 1. Note that if $\tilde{z} = \varepsilon$ and $\delta = n$, lifetime utility and the resource stock are both constant over time. This special case, represented by point S in Figure 1, satisfies most conventional notions of sustainability: utility is non-declining (standard definition), each generation enjoys the same welfare level (intergenerational equity), and natural capital as such is preserved over time (strong sustainability).

2.2 The economy with transfers

Proposition 1 suggests that if the economy is unsustainable under laissez-faire, a *ceteris paribus* reduction in z_t due to intergenerational transfers will bring the economy towards the sustainability threshold. Balanced budget policies with positive taxes affect the gap $(z_t - \tilde{z})$ unambiguously: from (15) and (20), the natural capital-resource asset ratio at time t equals

$$z_t = \tilde{z}\,(1-\tau_t)\,(1-d_t)\,. \tag{24}$$

Assume that the policymaker aims at achieving a pre-determined level z'. Substituting (24) in the government budget constraint (11), the target level $z_t = z'$ is obtained by setting $d_t = d'$ and $\tau_t = \tau'$, where (see Appendix)

$$d' = \left(\tilde{z} - z'\right)(1+\tilde{z})^{-1} \text{ and } \tau' = \left(\tilde{z} - z'\right)\left[\tilde{z}\left(1+z'\right)\right]^{-1}. \tag{25}$$

For example, setting $z' = \varepsilon$ in (25) yields tax-subsidy rates that implement zero depletion of the resource stock. By the same reasoning,

Lemma 2 *Setting* $d_t = \frac{\tilde{z}-\rho}{1+\tilde{z}}$ *and* $\tau_t = \frac{\tilde{z}-\rho}{\tilde{z}(1+\rho)}$ *for each* $t \in [0,\infty)$ *implies* $z_t = \rho$ *and* $U_{t+1} = U_t$ *for each* $t \in [0,\infty)$.

More generally, any fiscal intervention that keeps z_t below the laissez-faire level $\tilde{z}$ constitutes a *resource-saving policy*: lowering the natural capital-resource assets ratio corresponds to lower rates of resource use in production, or equivalently, to a higher degree of preservation.

3 Resource-saving transfers and lifetime welfare

We now compare the effects of laissez-faire and transfers on individual welfare in each period: in this regime-contingent formulation, individual payoffs represent the potential political support for resource-saving measures, as if agents were asked to choose between laissez-faire and intergenerational transfers during their life. Assuming that each newborn agent takes the history of previous regimes as given, we show that resource-saving transfers in both periods of life may yield higher payoffs with respect to persistent laissez-faire if a precise condition regarding technological parameters is satisfied.

3.1 Regime-contingent payoffs

Denote by η_t the outcome of an unspecified political process, indicating whether laissez-faire or resource-saving transfers are implemented in period t :

$$\eta_t = \begin{cases} 0 \Leftrightarrow & z_t = \tilde{z} \qquad (\textit{laissez-faire}) \\ 1 \Leftrightarrow & z_t = z' < \tilde{z} \quad \text{(res.-saving transfers)} \end{cases} \tag{26}$$

The individual payoff V_t of each agent born in $t \geq 0$ depends on the two outcomes realized during his lifetime (η_t and η_{t+1}) as well as on the whole history of previous outcomes $H_t = \left\{\eta_0, \eta_1, ..., \eta_{t-1}\right\}$:

$$V_t\left(\eta_t, \eta_{t+1}, H_t\right) = U_t\left[c_t\left(\eta_t, H_t\right), e_{t+1}\left(\eta_t, \eta_{t+1}, H_t\right)\right]. \tag{27}$$

Since agents cannot modify previous outcomes, H_t is taken as given and the individual payoff of an agent born in $T \geq 0$ can be written as (see Appendix)

$$V_T\left(\eta_T, \eta_{T+1}, H_T\right) = \Omega_T\left(H_T\right) + \log\left\{\left(\frac{z_T}{1+z_T}\right)^{\alpha}\left[\frac{(1+\rho)\,z_{T+1}}{(1+z_T)\,(1+z_{T+1})}\right]^{\alpha\beta}\right\}. \tag{28}$$

Suppressing argument H, we set $V_T(\eta_T, \eta_{T+1}, H_T) = V_T(\eta_T, \eta_{T+1})$ and compute all possible payoffs on the basis of (28). In particular, we will refer to $V_T(0,0)$ and $V_T(1,1)$ as payoffs yielded by *life-persistent regimes* ($\eta_t = \eta_{t+1}$). In the Appendix, we show that for any value of $z' < \tilde{z}$,

$$V_T(0,0) > V_T(0,1) \tag{29}$$

$$V_T(1,0) > V_T(1,1). \tag{30}$$

On the one hand, this result is intuitive: inequalities (29) and (30) imply that if agents could modify η_{T+1} while taking η_T as given, they would have an incentive to avoid taxation in the second period of life. On the other hand, (29) and (30) do not rule out situations where selfish agents would prefer persistent transfers to persistent laissez-faire: $V_T(1,1)$ and $V_T(0,0)$ cannot be ranked a priori, so it is possible to have the interesting case

$$V_T(1,0) > V_T(1,1) > V_T(0,0) > V_T(0,1). \tag{31}$$

The explicit condition for obtaining (31) is derived below.

Proposition 3 *Individual payoffs are ranked as in (31) if and only if*

$$\left(\alpha \frac{1+\beta}{\beta+\alpha}\right)^{1+\beta} \left(\beta \frac{1-\alpha}{\beta+\alpha}\right)^{\beta} < \left(\frac{z'}{1+z'}\right)^{1+\beta} (1+z')^{-\beta}. \tag{32}$$

Condition (32) is necessary and sufficient to have $V_T(1,1) > V_T(0,0)$, i.e. private agents strictly prefer life-persistent transfers to persistent laissez-faire. For a given discount factor β, inequality (32) defines the set of all possible combinations of α and z' implying $V_T(1,1) > V_T(0,0)$. This set can be characterized by defining the policy index $\mu \equiv z'/\tilde{z}$, which is determined by fiscal authorities through the level of tax-subsidy rates: from (24), the policy index equals $\mu = (1-\tau)(1-d)$, and $\mu < 1$ indicates a resource-*saving* policy. As shown in the Appendix, the welfare gap $\Phi = V(0,0) - V(1,1)$ can be written as

$$\Phi = \log \left\{ \left(\frac{1}{\mu}\right)^{\alpha+\alpha\beta} \left[\frac{\beta(1-\alpha) + \mu\alpha(1+\beta)}{\beta(1-\alpha) + \alpha(1+\beta)}\right]^{\alpha+2\alpha\beta} \right\}, \tag{33}$$

For given discount factors and policy targets, the gap function $\Phi(\alpha)$ has an inverted-U shape: as shown in Figure 2.a, there exists a critical value α^* such that $\Phi(\alpha^*) = 0$, with Φ being negative (positive) when the resource share exceeds (falls short of) this threshold level. In other words, *if the resource share exceeds the threshold value, lifetime utility is higher with persistent transfers than under laissez-faire conditions.* The economic interpretation of this result is as follows: reducing the rate of resource depletion in t implies higher output growth in $t+1$; if resource productivity is sufficiently high, this favorable effect on second-period income offsets the negative effect due to taxation.

Note that the critical level of the resource share depends on policy targets: as shown in Figure 2.b, α^* is higher the lower is μ. This is because μ is lower the higher is the level of transfers: if fiscal authorities impose slight deviations from laissez-faire (μ close to 1), the private cost of transfers is relatively small and condition (32) is likely to be met; conversely, if the policymaker is more inclined towards natural preservation

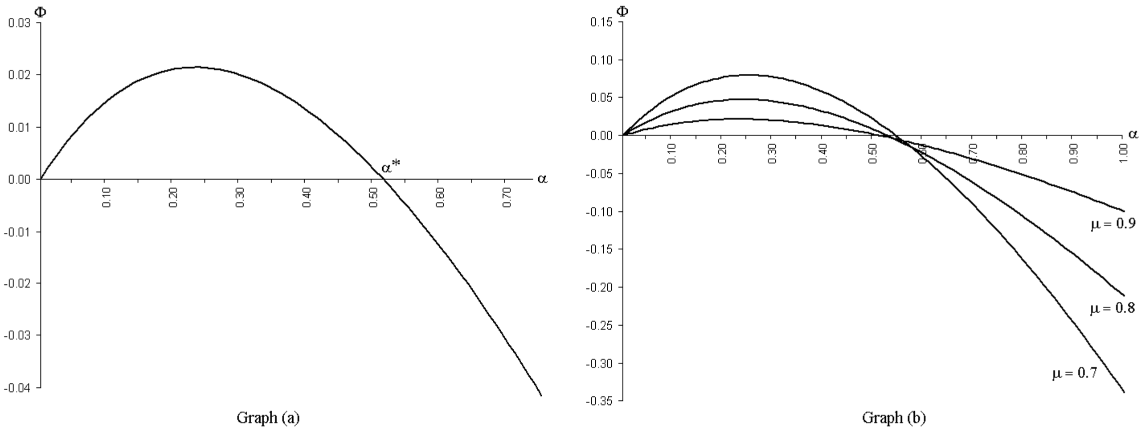

Figure 2: Graph (a): fixing $\beta = 0.95$ and $\mu = 0.9$, the gap $\Phi = V(0,0) - V(1,1)$ is an inverted-U function of α. Condition (32) defines the interval $(\alpha^*, 1)$ over which $V(1,1) > V(0,0)$. Graph (b): the welfare gap as a parametric function of $\mu = \{0.7, 0.8, 0.9\}$. The critical threshold increases as μ declines.

(μ close to 0), persistent transfers are more demanding and condition (32) is more restrictive.

From a policymaking perspective, the result that permanent transfers may be welfare improving for *present* generations is relevant. In particular, ranking (31) suggests that while individual preferences about policy regimes can be in favor of intergenerational transfers, this private desire for resource-saving policies unfolds if generations are credibly pre-committed. This statement is investigated in section 3.3 and is similar to a standard result in the literature on pension funding: in the absence of commitment technologies, selfish agents would not implement pay-as-you-go social security systems (Browning, 1975; Hammond, 1975). An important difference, however, is that resource-saving policies involve an opposite direction of transfers (old-to-young) with respect to social security systems (young-to-old), so that commitment technologies must take a different form. In social security systems, young agents agree on first-period taxation only if convinced that they will receive second-period transfers; in the present model, instead, resource-saving measures gain unanimous support only if young agents receiving subsidies in the first period are induced to pay second-period taxes. As a consequence, full political support for resource-saving transfers requires either credible pre-commitment, or cooperation among adjacent generations. An example of a commitment device is provided by lifetime contracts (sec.3.3). In a sequential choice setting, instead, cooperation can be induced by positive costs of regime-switching (sec.3.4). Before discussing these issues, we complete the analysis of distortionary transfers by comparing first-best and second-best policies for intergenerational equity.

3.2 First-best and second-best policies

In order to assess the effects of distortionary transfers on allocative efficiency, a convenient benchmark is to assume that the policy target is to achieve intergenerational equity. In this case, the first best (Rawlsian optimum) requires two conditions to be satisfied: first, all generations enjoy the same utility level U^*; second, U^* must be the maximum utility level that can be sustained indefinitely. The first condition requires constant income per capita, and hence $m_t x_t$ constant over time (see Appendix):

$$x_t^* = \left(\frac{1}{1+\delta}\right)^t \frac{\rho}{1+\rho} r_0, \quad r_t^* = \left(\frac{1}{1+\delta}\right)^t r_0. \tag{34}$$

The depletion path (34) implies a constant output level $y^* = \left[\rho\,(1+\rho)^{-1}\, m_0 r_0\right]^\alpha$. The second condition requires (see Appendix)

$$c_t = c^* = (1+\beta)^{-1}\, y^*, \quad e_t = e^* = \beta\,(1+n)\,(1+\beta)^{-1}\, y^*. \tag{35}$$

Hence, along the first-best path, utility equals

$$U^* = \log\left\{[\beta\,(1+n)]^\beta \left[y^*\,(1+\beta)^{-1}\right]^{1+\beta}\right\} \tag{36}$$

for all agents born in $t \geq 0$. If the government aims at implementing the Rawlsian optimum, a *first-best policy* is one that decentralizes the allocation described by (34)-(35). A crucial feature of this economy is that the first-best policy cannot rely on a lump-sum transfer scheme alone, due to the asymmetric intergenerational distribution of property rights over natural resources. Exactly as in Mourmouras (1993), achieving the first-best requires expropriating natural capital of the initial old generation: at $t = 0$ the whole resource stock is nationalized; old agents at $t = 0$ receive a stock of fiat currency that will be transferred to successive generations when acquiring output units; at each $t \geq 0$, the government sells x_t^* units of resources to firms, and rebates the proceeds to the young generation via lump-sum transfers. This policy decentralizes the Rawls-optimal allocation, and lifetime welfare of all agents born in $t \geq 0$ is given by (36).[5]

The fact that, under the first-best policy, the initial old generation is expropriated is of particular interest here. In section 3.1, distortionary policies aimed at reducing the rate of resource use also imply a welfare reduction for the initial old. In order to compare the two policies, consider a couple of tax-subsidy rates that implements a constant-utility path. Such a policy is that considered in Lemma 2: authorities set $z' = \rho$ in each period, and obtain the same depletion paths (34). With $x_t = x_t^*$, output equals $y_t = y^*$ in each period. However, with respect to the Rawlsian optimum, consumption is lower in the first period and higher in the second:[6]

$$c_t = c^{**} = (1-\alpha)\,(1+\beta)^{-1}\, y^* < c^*, \tag{37}$$

$$e_t = e^{**} = (\alpha+\beta)\,(1+n)\,(1+\beta)^{-1}\, y^* > e^*. \tag{38}$$

[5] See proof in the Appendix. With respect to Mourmouras (1993), this Rawls-optimal program differs because of the presence of technical progress, which has two interrelated implications: first, natural capital per capita x_t^* declines over time, instead of being constant; second, while utility is kept at constant level, the resource stock R_t can be either declining, constant, or increasing: as explained in section 2.1, when production possibilities are increased through m, intergenerational equity and resource preservation are distinct concepts, and the long-run value of the resource stock depends on the gap between the rates of technical progress and population growth (cf. Figure 1).

[6] Equations (37)-(38) derive from conditions (A2)-(A3) in the Appendix.

From (36) and (37)-(38), lifetime welfare $U^{**}(c^{**}, e^{**})$ under this policy is lower with respect to the first-best:

$$U^* - U^{**} = \log\left\{(1-\alpha)^{-1}\left[\beta/(\alpha+\beta)\right]^{\beta}\right\} > 0. \tag{39}$$

Expression (39) is the welfare loss experienced by every agent born in $t \geq 0$ under second-best policies. However, the two policies cannot be Pareto ranked: from (38), the utility level of the first old generation is higher under the second-best policy. Put differently, if agents face an exclusive choice between the two policies, the young prefer the first-best scheme with nationalization of the resource stock, whereas the old are better off under distortionary transfers.

3.3 Lifetime contracts

It follows from Proposition 3 that, when (32) is satisfied, if agents are asked at birth to sign a *lifetime contract* requiring them to choose between persistent transfers and persistent laissez-faire, every agent born in $t \geq 0$ chooses resource-saving transfers. With respect to this result, three main points should be emphasized. First, lifetime contracts embody a notion of credible commitment: under ranking (31), agents prefer resource-saving transfers as long as no regime switch is allowed during the life-cycle. Second, private agents would not enforce such contracts by themselves because resource owners at $t = 0$ receive no compensation: this is the 'first-father problem' discussed below. Third, whether a sustainable path would be supported depends on the whole set of parameters. Suppose that lifetime contracts include the options $\tilde{z} > \rho$ and $z' = \rho$. If condition (32) holds, agents choose z' and lifetime contracts support a constant utility path. As shown in Figure 2.b, the technological condition is more restrictive the lower is μ: that is, the threshold α^* is very high when the 'sustainability gap' $(\tilde{z} - \rho)$ is substantial, whereas conditions for an agreement on sustainability are less restrictive when $\tilde{z}$ is relatively close to ρ. However, section 4 shows that when other financial assets exist in the economy, the critical threshold for the resource share is reduced, and its sensitivity to policy targets becomes less critical in this regard.

When considering an infinite time horizon, the individual first-best payoff cannot be assigned to each generation, since implementing $V_t(1,0)$ in each t is impossible. From a social-planning perspective, the relevant inequality in (31) is thus the central one, $V(1,1) > V(0,0)$, which refers to life-persistent regimes. This in turn suggests studying the welfare time-paths implied by the sequences $\{\tau_t = 0, d_t = 0\}_{t=0}^{\infty}$ and $\{\tau_t = \tau', d_t = d'\}_{t=0}^{\infty}$. We refer to these sequences as *permanent laissez-faire* and *permanent transfers*, respectively. Since the initial resource stock is owned by the old at time zero, a typical 'first-father problem' arises: if transfers are voted into existence at $t = 0$, all successive generations gain from permanent transfers, but initial subsidies are financed at the expense of the first old generation. This generation bears the burden of the new regime without gaining from it, and welfare improvements thus pertain to *newborn* agents. On the one hand, the first-father problem implies that the two sequences, permanent laissez-faire and permanent transfers, cannot be Pareto ranked. On the other hand, resource-saving policies recall the logic of Gale-type intergenerational transfers: considering a two-generations pure exchange economy, Gale (1973) showed that the first generation can raise future welfare by renouncing part of its claim over the endowment to the benefit of the second generation, which in turn transmits a claim to its successor, and so on. In our setting, transfers work in a similar way: the initial tax $\tau_0 p_0 X_0$ amounts to the share of claims over natural capital not received by the first owner, and subsidies to the newborn bring the associated credit forward in time.

3.4 Sequential voting and induced cooperation

With lifetime contracts, resource-saving policies are supported by successive generations because agents are credibly committed to pay second-period taxes. An alternative interpretation of Proposition 3 derives from assuming a sequential process generating political decisions. Suppose that fiscal authorities act in a representative democracy, and implement the regime voted by the citizens *in each period*: in this case, all individuals alive in period t face a discrete choice between laissez-faire ($z_t = \tilde{z}$), and a certain amount of transfers corresponding to the policy proposed by fiscal authorities ($z_t = z' < \tilde{z}$). For a given voting rule, the sequence of depletion rates is determined by the outcomes of an indefinitely repeated game. Similar games are used in the recent literature on social security systems and political economy (Cooley and Soares, 1998; Boldrin and Rustichini, 2000; Azariadis and Galasso, 2002). These contributions study whether pay-as-you-go social security systems may result from political equilibria when private agents choose to create, maintain, or dismantle intergenerational transfers. A similar reasoning will be followed here, the main difference being that the direction of transfers implied by pension financing (young-to-old) is opposite to that implied by resource-saving policies (old-to-young). In particular, the different configuration of payoffs in the present model implies the following

Lemma 4 *If (32) holds, agents support transfers in their first period of life in any subgame perfect equilibrium sequence.*

The intuition for this result follows immediately from (31): in the first period, laissez-faire choices are ruled out by the fact that young agents prefer resource-saving transfers *irrespective* of second-period outcomes. The difference with respect to social-security games is twofold. On the one hand, Lemma 4 departs from the result, established by Boldrin and Rustichini (2000: p.51), that laissez-faire outcomes can be part of an equilibrium sequence in pension games (see Appendix). On the other hand, Lemma 4 implies that in a growing economy ($n > 0$), *simple-majority rules* suffice to obtain permanent transfers ($\eta_t = 1$ in each $t \geq 0$) as a political equilibrium,[7] in contrast with the standard result that the open-loop equilibrium in pension games features permanent laissez-faire (Hammond, 1975; Sjoblom, 1985; Azariadis and Galasso, 2002).[8] More generally, the configuration of payoffs in (31) implies that coexisting generations never cooperate. To see this, consider a *qualified-majority rule* - that is,

[7] As in Azariadis and Galasso (2002), consider a simple-majority rule operating among homogeneous agents within each cohort: if the net rate of population growth is positive (negative), the majority of citizens is constituted by young (old) agents. Sincere voting thus implies that the political outcome η_t coincides with the action of the young when $n > 0$. As a consequence, when the critical condition (32) is satisfied, if $n > 0$ resource-sacing transfers are voted into existence from $t = 0$ onward, whereas, if $n < 0$, the political outcome is permanent laissez-faire.

[8] The intuition for this result is that, in pension games, young agents - the majority of citizens in a growing economy - do not finance current pensions (young-to-old transfers) in the absence of commitment devices binding the next generation (see e.g. Azariadis and Galasso, 2002).

if both cohorts vote for a given regime in t, this regime will be established; otherwise, the previous regime is maintained ($\eta_t = \eta_{t-1}$).[9] In this case, any regime established at $t = 0$ becomes a self-sustained regime irrespective of the population growth rate:

Lemma 5 *Under qualified-majority voting, if (32) holds then $\eta_t = \eta_0$ in each $t > 0$.*

It follows from the above discussion that intergenerational compromise lacks as long as old agents have no incentives to cooperate with the currently young. In this regard, it is worth noting that cooperative voting may be induced by a positive cost of regime-switching. More precisely, in the present model, a transfer regime already in place is sustained indefinitely with unanimous consensus, provided that a regime switch involves a relevant cost for all agents. Note that the presence of regime-switching costs is consistent with two alternative interpretations: it may reflect an exogenous (e.g. administrative) cost of reforms, or represent an 'over-rule tax'. In either case, the analysis of payoffs is identical: assume that $\eta_{t-1} = 1$ at some $t > 0$, and denote by $\epsilon_t\left(\eta_{t-1}\right)$ the welfare cost of a regime switch in period t. The new lifetime payoffs for young agents in period t, conditional on $\eta_{t-1} = 1$, are denoted by $\bar{V}_t$ and read

$$\begin{aligned} \bar{V}_t(0,0) &= V_t(0,0) - \epsilon_t(1), \\ \bar{V}_t(0,1) &= V_t(0,1) - \epsilon_t(1) - \beta\epsilon_{t+1}(0), \\ \bar{V}_t(1,0) &= V_t(1,0) - \beta\epsilon_{t+1}(1), \\ \bar{V}_t(1,1) &= V_t(1,1), \end{aligned} \tag{40}$$

and the following result can be established:

Lemma 6 *If*

$$\epsilon_t(1) > \Phi \tag{41}$$

and

$$\epsilon_{t+1}(1) > \log\left(\frac{1+\mu\tilde{z}}{\mu+\mu\tilde{z}}\right)^{\alpha}, \tag{42}$$

agents born in t support transfers in both periods of life. If (41)-(42) hold at all $t \geq 0$, setting $\eta_0 = 1$ implies unanimous support for transfers at all future dates.

The reasoning behind Lemma 6 is that when the loss implied by a regime switch is sufficiently high, permanent transfers become the first-best individual payoff: in fact, satisfying condition (42) implies $\bar{V}_t(1,1) > \bar{V}_t(1,0)$, so that agents will vote for resource-saving transfers not only when young (in t), but also when old (in $t+1$). With respect to this result, we can make three remarks. First, Lemma 6 does not assume that the usual critical condition be satisfied, since condition (41) is sufficient to have $\bar{V}_t(1,1) > \bar{V}_t(0,0)$, and is less restrictive than (32).[10] Second, the cost of regime-switching is assumed to be time-varying and regime-contingent for the sake of generality: if it is interpreted as an exogenous administrative cost, further assumptions

[9] This voting mechanism is used in many countries, e.g. while voting to modify constitutional norms, in order to guarantee that specific norms are also accepted by at least a fraction of parties that usually oppose the 'standard majority'.

[10] In fact, the critical condition (32) implies $\Phi < 0$, but (41) can be satisfied even if $\Phi > 0$. That is, the presence of regime-switching cost may ensure that persistent transfers are strictly prefer to laissez-faire conditions even if $\Phi > 0$.

yield symmetry in states (i.e. going from laissez-faire to transfers is as costly as doing the opposite reform) and stationary costs, in which case conditions (41)-(42) can be expressed in terms of exogenous parameters. Third, the cost of regime-switching can be alternatively interpreted as an over-rule tax, which essentially constitutes a commitment technology for young generations.

More generally, in the vast majority of sequential games, a paternalistic action at $t = 0$ is required to induce permanent resource-saving transfers . It should be stressed, however, that this variant of the 'first-father problem' does not originate in the distortionary character of transfers: recalling the results of section 3.2, the amount of resources subtracted from the initial old is even higher under a first-best policy: if the first father faced an exclusive choice between first- and second-best policies, he would vote for distortionary transfers, in order to avoid expropriation of his natural capital.

4 Capital, monopoly rents and R&D activity

The basic model is now extended to include other assets, in addition to natural capital, which represent individual wealth. In this section, we derive critical conditions that are conceptually analogous to (32), in the presence of (i) man-made capital, (ii) monopolistic sectors, and (iii) R&D firms developing innovations. For simplicity, we rule out population growth ($n = 0$) and normalize total labor supply to unity ($N_t = 1$). Exogenous technical progress is also ruled out ($\delta = 0$), since we will introduce endogenous technical change under a slightly different production function.

4.1 Man-made capital

With $\delta = 0$, the model with man-made capital is essentially that in Mourmouras (1993: sect.6), with the only addition of distortionary transfers. Aggregate output is now given by $Y = X^{\alpha_1} N^{\alpha_2} K^{\alpha_3}$ with constant returns to scale ($\alpha_1 + \alpha_2 + \alpha_3 = 1$). Output per capita equals

$$y_t = x_t^{\alpha_1} k_t^{\alpha_3}, \tag{43}$$

where $k \equiv K/N$ is individual capital. Agents born in t may allocate savings in assets representing either natural or man-made capital, with budget constraints

$$c_t = w_t - q_t a_t (1 - d) - k_{t+1}, \tag{44}$$
$$e_{t+1} = q_{t+1} a_{t+1} + p_{t+1} (1 - \tau) x_{t+1} + i_{t+1}^k k_{t+1}, \tag{45}$$

where i_{t+1}^k is the interest factor received when adult. Tax and subsidy rates (d, τ) are constant and set compatibly with balanced budget in each period, implying the aggregate constraint

$$k_{t+1} = y_t - c_t - e_t. \tag{46}$$

Utility maximization yields the standard Euler condition

$$e_{t+1} = \beta c_t i_{t+1}^k, \tag{47}$$

whereas maximization of lifetime income requires

$$c_t = w_t (1 + \beta)^{-1} = \alpha_2 (1 + \beta)^{-1} y_t \tag{48}$$

and the Hotelling rule

$$\frac{q_{t+1}}{q_t} = i_{t+1}^k \left(\frac{1-d}{1+\varepsilon} \right) \tag{49}$$

be satisfied. The equilibrium propensity to invest is now affected by the capital share α_3, which in turn modifies the depletion index $z_t = x_t/a_t$. Assuming a sequence of constant tax-subsidy rates, z_t is constant over time, and given by (see Appendix)

$$\alpha_3 \left(\frac{1-d}{1+z} \right) + \frac{\alpha_1}{z} (1-d)(1-\tau) - \frac{\alpha_2 \beta}{1+\beta} = 0. \tag{50}$$

Expression (50) is a quadratic equation in z with only one admissible (positive) root. With $d = \tau = 0$, the same procedure gives the laissez-faire value $\tilde{z}$. As in the basic model, equilibrium dynamics of natural capital and resource assets imply a constant rate of depletion of the resource stock

$$\theta_{t+1}^x = \theta_{t+1}^a = \theta_{t+1}^r = (1+\varepsilon)(1+z)^{-1},$$

whereas output and man-made capital evolve according to[11]

$$\theta_{t+1}^k = \alpha_3 \left(\frac{1-d}{1+z} \right) x_t^{\alpha_1} k_t^{\alpha_3 - 1}, \tag{51}$$

$$\theta_{t+1}^y = \left(\theta_{t+1}^x\right)^{\alpha_1} \left(\theta_{t+1}^k\right)^{\alpha_3}. \tag{52}$$

As shown in the Appendix, man-made capital and output converge to the same (constant) growth rate in the long run

$$\lim_{t\to\infty} \theta_t^y = \left[(1+\varepsilon)/(1+z)\right]^{\frac{\alpha_1}{1-\alpha_3}}, \tag{53}$$

and the interest factor approaches the steady-state value

$$\lim_{t\to\infty} i_t = (1+z)\left[(1+\varepsilon)/(1+z)\right]^{\frac{\alpha_1}{1-\alpha_3}}. \tag{54}$$

Expression (53) shows that a reduction in z increases the long term growth rate more intensively the higher the capital share α_3. This suggests that the presence of capital improves the effectiveness of resource-saving policies in sustaining welfare over time. To address this point, consider a policy target $\mu = z'/\tilde{z} < 1$ which corresponds to a couple of tax-subsidy rates satisfying the government budget constraint (11). As shown in the Appendix, the condition for obtaining $\Phi < 0$ is now

$$\left(\frac{1+\mu\tilde{z}}{\mu+\mu\tilde{z}} \right)^{\alpha_1 + \alpha_1\beta(1+\alpha_3)} \left(\frac{1+\mu\tilde{z}}{1+\tilde{z}} \right)^{\alpha_1\beta} < 1. \tag{55}$$

With respect to the basic model of section 3.1, a slight complication is that $\tilde{z}$ is not linear in α_1, and the critical condition for the resource share must be obtained numerically. Results differ substantially from the predictions of the basic model: in the labor-resource economy of section 3.1, condition (32) is usually met for values of the resource share exceeding 0.5 - a rather high value, from an empirical perspective. In the

[11] Equation (51) is obtained by substituting $y_t = x_t^{\alpha_1} k_t^{\alpha_3}$ in equation (A36) in the Appendix. Equation (52) follows from $y_t = x_t^{\alpha_1} k_t^{\alpha_3}$ and the transition law $x_{t+1}(1+z) = x_t(1+\varepsilon)$.

present model, instead, capital productivity affects condition (55) through α_3, and the critical threshold is far below 0.5 under reasonable parameters. In the example reported in Table 1, we fix $\alpha_2 = 0.4$ and let α_1 and α_3 vary with a 5% discount rate ($\beta = 0.95$). The critical resource share is $\alpha_1^* \simeq 0.23$ with 'light policies' ($\mu = 0.9$), and increases with heavier tax-subsidy rates ($\alpha_1^* \simeq 0.37$ with $\mu = 0.7$). The interpretation of this result is that the presence of capital enhances the mechanism via which first-period subsidies may compensate, in terms of utility, the negative effects of second-period taxation: the reduction in resource depletion in t increases output levels in $t+1$, with a positive level effect on private returns from natural *and* man-made capital. The next section shows that this conclusion is robust to alternative assumptions regarding the nature of financial assets held by private agents.

4.2 Monopoly rents

In this section we substitute man-made capital with assets representing claims over future monopoly rents. This framework will be extended in sec.4.3 to include endogenous technical change generated by R&D activity. The supply side of the economy now consists of producers of final output (Y) and firms producing intermediate products (B). Final output is obtained by means of natural capital, labor and a number g (assumed exogenous, for the moment) of intermediate goods' varieties. Assuming constant population, and denoting by $B_{(j)}$ the quantity of the j-th variety of intermediate inputs ($j = 1, ..., g$), output equals

$$Y_t = X_t^{\nu_1} N^{\nu_2} \sum_{j=1}^{g} B_{(j),t}^{\nu_3}, \tag{56}$$

where $\nu_1 + \nu_2 + \nu_3 = 1$. Each variety is produced by a monopolist with unit production cost. Denoting by $p_{(j)}^b$ the price of intermediates, each monopolist maximizes profits $\bar{\pi}_{(j)} = B_{(j)} p_{(j)}^b - B_{(j)}$ taking the demand schedule of final producers as given. First order conditions imply $p_{(j)}^b = \nu_3^{-1}$ in each period, so that prices and quantities of intermediates are invariant across varieties. As a consequence, each monopolist produces

$$B_t = B_{(j),t} = \left(\nu_3^2 X_t^{\nu_1} N^{\nu_2}\right)^{\frac{1}{1-\nu_3}}. \tag{57}$$

Monopolistic firms are owned by the currently old generation. Old agents in period t thus receive the per capita profit rate

$$g\pi_t = (g/\nu_3)(1 - \nu_3)\, b_t, \tag{58}$$

where $\pi_t = \bar{\pi}/N$ and $b_t \equiv B_t/N$. Note that (57) and (58) imply that output grows at the same rate as intermediate quantities and monopoly profits:

$$y_t = \nu_3^{-2} g b_t, \qquad \theta_t^y = \theta_t^b = \theta_t^\pi. \tag{59}$$

Each firm producing a variety holds the relevant patent, and old agents control the exclusive right to produce existing intermediate goods. Since agents die after the second period, young agents buy patents in period t in order to run monopolistic firms in $t+1$. This is equivalent to assuming that young agents invest in single-period obligations of a consolidated intermediate sector, representing claims over future monopoly profits. Denote by $v_{(j),t}$ the *forward patent value*, i.e. the value in period t of a patent exploitable to produce the j-th variety in period $t+1$. Since profits are invariant across varieties, $v_{(j),t} = v_t$ for any $j \in [1, g]$. The aggregate value of all patents in the intermediate sector is $F_t \equiv g v_t$, and individual budget constraints read

$$c_t = w_t - q_t a_t (1-d) - f_t, \tag{60}$$
$$e_{t+1} = p_{t+1} x_{t+1} (1-\tau) + q_{t+1} a_{t+1} + g\pi_{t+1} + f_{t+1}, \tag{61}$$

where $f \equiv F/N$ is the per capita cost of patents. The aggregate constraint of the economy is (see Appendix):

$$y_t = c_t + e_t + g b_t. \tag{62}$$

Optimality conditions for consumers imply the Hotelling condition

$$\frac{q_{t+1}}{q_t}\left(\frac{1+\varepsilon}{1-d}\right) = i^f_{t+1}, \tag{63}$$

where the implicit interest factor is defined as the gross return on assets

$$i^f_{t+1} = (\pi_{t+1} + f_{t+1}) / f_t. \tag{64}$$

As shown in the Appendix, the natural capital-resource asset ratio is constant in equilibrium, and equals

$$z = (1-d)\left[\left(1-\nu_3^2\right)(1+\beta) - \nu_2\right](\nu_2\beta)^{-1} - 1. \tag{65}$$

A constant propensity to invest in resources implies a knife-edge equilibrium: the economy displays constant rates of resource use and output growth. In particular, since $\theta^y_t = \theta^b_t$, we have

$$\theta^y_t = (\theta^x_t)^{\nu_1}\left(\theta^b_t\right)^{\nu_3} = (\theta^x_t)^{\frac{\nu_1}{1-\nu_3}} = [(1+\varepsilon)/(1+z)]^{\frac{\nu_1}{1-\nu_3}}. \tag{66}$$

Similarly to the model with capital - see (53) - the presence of intermediates contributes to the magnitude of the growth effects induced by resource-saving policies: transfers increase θ^y by reducing z, and the exponent in (66) is increasing in the intermediates share ν_3. The dynamic interaction between resource use and investment in intermediate firms is as follows. The rate of depletion θ^x determines output growth θ^y, which is in turn the rate at which monopoly rents develop over time - see (59). Hence, reducing the rate of resource use sustains not only output, but also the profitability of monopolistic firms that represent investment opportunities for young agents. We thus expect a positive influence of ν_3 on the critical condition for $\Phi < 0$. As shown in the Appendix, the welfare gap $V(0,0) - V(1,1)$ now reads

$$\Phi = \log\left\{\left(\frac{1}{\mu}\right)^{\frac{\nu_1(1+\beta)}{1-\nu_3}}\left(\frac{1+\mu\tilde{z}}{1+\tilde{z}}\right)^{\frac{\nu_1(1+2\beta)}{1-\nu_3}}\right\}, \tag{67}$$

where $\tilde{z}$ is given by setting $d=0$ in (65). Looking at Table 1, numerical substitutions suggest that, with respect to the model with capital, monopoly rents imply $\Phi < 0$ for a wider range of parameters: considering different policy targets (μ) and comparable values of input shares, the critical threshold with monopoly rents (ν_1^*) is lower than that obtained with capital (α_1^*). In the next section, the model with monopoly rents is extended to study the interaction between resource exploitation, endogenous technical change, and intergenerational fairness.

4.3 R&D activity

The previous model is now extended to include a third sector which develops innovations: R&D firms invent new varieties of intermediates, thereby increasing the number of monopolistic firms operating in the economy. We thus obtain a variant of the expanding-varieties model (see Barro and Sala-i-Martin, 2004), which includes overlapping generations and resource extraction. Aggregate output equals

$$Y_t = X_t^{\nu_1} N^{\nu_2} \sum_{j=1}^{g_t} B_{(j),t}^{\nu_3}, \tag{68}$$

where the number of intermediates' varieties, g_t, is now endogenous and generally time-varying. The behavior of monopolistic firms is as before, with profit-maximizing conditions implying $p_t^b = 1/\nu_3$ and

$$B_t = B_{(j),t} = \left(\nu_3^2 X_t^{\nu_1} N^{\nu_2}\right)^{\frac{1}{1-\nu_3}}. \tag{69}$$

From (68) and (69), equilibrium output per capita now reads

$$y_t = g_t x_t^{\nu_1} b_t^{\nu_3} = \nu_3^{-2} g_t b_t, \tag{70}$$

and equilibrium dynamics imply

$$\theta_{t+1}^y = \theta_{t+1}^g \theta_{t+1}^b, \qquad \theta_{t+1}^b = \left(\theta_{t+1}^x\right)^{\frac{\nu_1}{1-\nu_3}}. \tag{71}$$

R&D firms operating in period t invent new varieties that monopolistic firms will exploit at $t+1$. In order to develop $(g_{t+1} - g_t)$ new varieties, the R&D sector consumes $\bar{h}_t$ units of output, and the innovation technology takes the form

$$g_{t+1} - g_t = \xi_t \bar{h}_t, \tag{72}$$

where ξ_t, the marginal productivity of R&D expenditure, is affected by aggregate spillovers generating endogenous growth. In the R&D literature, spillovers are typically formalized as knowledge-stock externalities, implying that current R&D activity is more productive the better the state-of-the-art at the aggregate level. In the present model, a convenient index for the state-of-the-art in producing new intermediates is the number of existing varieties in relation to output levels. Assuming a linear relation between the marginal productivity of R&D firms and the state of technology index, the aggregate productivity of the R&D sector increases with the economy-wide rate of R&D investment:

$$\xi_t = \psi \left(\frac{g_t}{y_t}\right), \qquad \theta_{t+1}^g = 1 + \psi h^m, \tag{73}$$

where $\psi > 0$ is a proportionality factor, and $h^m \equiv \bar{h}_t / y_t$ is the rate of R&D investment determining, by (72), the rate of expansion in intermediates' varieties. Since profits are invariant across varieties, the value of each new blueprint equals the forward value of a patent v_t, and equilibrium in the R&D sector requires[12]

$$v_t = 1/\xi_t. \tag{74}$$

[12] Condition (74) maximizes profits $v_t\left(g_{t+1} - g_t\right) - \bar{h}_t$ and implies zero extra profits in the R&D sector. The same condition is equivalently obtained assuming free entry in the R&D business for an indefinite number of firms, as in Barro and Sala-i-Martin (2004: Chp.6).

From the households' point of view, R&D firms represent an additional asset: R&D investment in period t allows young agents to run $(g_{t+1} - g_t)$ new monopolistic firms in the subsequent period, obtaining higher second-period income through (i) additional monopoly profits from intermediates' production, and (ii) additional patent sales to newborn generations in $t + 1$. This mechanism is summarized by the individual constraints

$$c_t = w_t - q_t a_t (1-d) - f_t - h_t, \tag{75}$$
$$e_{t+1} = p_{t+1} x_{t+1} (1-\tau) + q_{t+1} a_{t+1} + g_{t+1} \pi_{t+1} + f_{t+1}, \tag{76}$$

where h_t is R&D investment per capita, and equals agents' expenditure to obtain patents for new intermediates: from (74), in aggregate we have

$$h_t = \bar{h}_t = (1/\xi_t)(g_{t+1} - g_t). \tag{77}$$

As regards revenues, non-resource income in (76) can be decomposed as

$$g_{t+1}\pi_{t+1} + f_{t+1} = [(g_{t+1} - g_t)(\pi_{t+1} + v_{t+1})] + g_t (\pi_{t+1} + v_{t+1}). \tag{78}$$

The last term in (78) is the sum of current profits and patent sales of the g_t firms that already existed in t, while the term in square brackets is the additional income (profits plus patents) generated by new blueprints, and thus represents the gross return to R&D investment. In equilibrium, the two returns must be equal, and the implicit interest factor is

$$i_{t+1}^h = \frac{g_t (\pi_{t+1} + v_{t+1})}{f_t} = \frac{(g_{t+1} - g_t)(\pi_{t+1} + v_{t+1})}{h_t}. \tag{79}$$

From (68), (75) and (76), the aggregate constraint now reads (see Appendix)

$$y_t = c_t + e_t + g_t b_t + h_t. \tag{80}$$

Optimality conditions for consumers yield the Hotelling rule

$$\frac{q_{t+1}}{q_t}\left(\frac{1+\varepsilon}{1-d}\right) = i_{t+1}^h, \tag{81}$$

and the standard Euler condition $e_{t+1} = \beta c_t i_{t+1}^h$. As shown in the Appendix, the propensity to invest in resources is constant, and the depletion index z is recursively determined by (the unique positive root of) the system

$$z = (1-d)\left[1 + \psi\nu_3 (1-\nu_3)\right]\left[1 + \psi h^m\right]^{-1} - 1, \tag{82}$$
$$h^m = \nu_2 \beta (1+\beta)^{-1} - \psi^{-1} - \nu_1 (1-d)(1-\tau) z^{-1}, \tag{83}$$

where the marginal propensity to invest in R&D, h^m, is constant as well. Hence, the equilibrium features balanced growth, and output per capita grows at the constant rate[13]

$$\theta^y = \theta^g (\theta^x)^{\frac{\nu_1}{1-\nu_3}} = (1 + \psi h^m)\left[(1+\varepsilon)/(1+z)\right]^{\frac{\nu_1}{1-\nu_3}}. \tag{84}$$

[13] Rewriting the innovation frontier as $\theta_{t+1}^g = 1 + \psi h^m$ and substituting in (71) we obtain (84).

Since consumption is proportional to output levels, the necessary and sufficient condition for non-declining welfare is now

$$(1+\psi h^m)\left[(1+\varepsilon)/(1+z)\right]^{\frac{\nu_1}{1-\nu_3}} \geq 1, \tag{85}$$

which confirms that prospect for sustainability are improved by endogenous technical change - here represented by the rate of expansion in intermediate varieties $\theta_{t+1}^g = (1+\psi h^m)$. The effect of intergenerational transfers on the growth rate is twofold. On the one hand, positive tax-subsidy rates reduce the depletion index z, implying the usual mechanism: from (84), a reduction in z directly increases the output growth rate θ^y, and this effect is stronger the higher are the shares of resources (ν_1) and intermediates (ν_3) in production. On the other hand, taxes and subsidies also affect the marginal propensity to invest in R&D, and thereby the rate of expansion in intermediate varieties $(1+\psi h^m)$. This second effect is generally ambiguous, but rather unlikely to imply a reduction of output growth following a decrease in the resource depletion rate.[14]

As shown in the Appendix, the critical condition for $\Phi < 0$ is now

$$\left(\frac{1}{\mu}\right)\left(\frac{1+\mu\tilde{z}}{1+\tilde{z}}\right)^{\frac{1+2\beta}{1+\beta}} > 1, \tag{86}$$

with numerical results reported in Table 1. For the different policy targets considered, the critical levels of the resource share in the R&D model occupy intermediate positions if compared with previous models: with R&D activity, the critical threshold ν_1^* is slightly higher than that obtained with monopoly rents, but lower than that obtained in the model with man-made capital (cf. Table 1). Notice, however, that a sustainability-targeted policy is more politically feasible *with* R&D activity: the reason is that sustainability conditions differ between the present model and that with monopoly rents - see (66) and (84) - and the growth rate in the economy with R&D is generally higher. Hence, achieving sustainability in the R&D economy involves a smaller deviation from laissez-faire (that is, a higher μ) with respect to the economy with monopoly rents, which grows less and must fill a bigger sustainability gap (that is, requires a lower μ). As a consequence, the critical threshold becomes less restrictive for the economy with R&D firms.[15]

[14] The effect of a variation in tax-subsidy rates on h^m is generally ambiguous since a variation in d and τ modify both the numerator and denominator in the last term in (83). However, an interior equilibrium with positive R&D activity requires $\psi > 1$ (see Appendix: eq.A55), and this implies that possible reductions in h^m would not reduce the rate of expansion $1+\psi h^m$ substantially. The net effect of a reduction in z on output growth thus remains largely determined by the usual mechanism induced by resource preservation.

[15] For example, set $\nu_1 = 0.25$, $\nu_3 = 0.35$, and suppose that the R&D economy requires a reduction of the depletion index corresponding to $\mu = 0.9$. Recalling (66) and (84), the R&D economy can be safely assumed to be growing faster than a no-R&D economy with monopoly rents. The latter economy thus requires higher levels of tax-subsidy rates to achieve sustainability, corresponding to (e.g.) $\mu = 0.7$. Under these parameters ($\nu_1 = 0.25$, $\nu_3 = 0.35$), Table 1 shows that the sustainability policy would be politically supported in the R&D economy ($\Phi^R = -.0003$ with $\mu = 0.9$) while it would not be in the no-R&D economy ($\Phi^M = .0003$ with $\mu = 0.7$).

Input shares			$\mu = 0.9$			$\mu = 0.8$			$\mu = 0.7$		
ν_1	ν_2	ν_3	Φ^M	Φ^R	Φ^K	Φ^M	Φ^R	Φ^K	Φ^M	Φ^R	Φ^K
.15	.40	.45	.0011	.0097	.0010	.0047	.0252	.0036	.0119	.0489	.0084
.20	.40	.40	-.0009	.0039	.0005	.0008	.0128	.0029	.0065	.0289	.0081
.25	.40	.35	-.0031	-.0003	-.0003	-.0035	.0037	.0016	.0003	.0140	.0067
.30	.40	.30	-.0053	-.0035	-.0014	-.0078	-.0033	-.0004	-.0060	.0025	.0042
.35	.40	.25	-.0073	-.0060	-.0028	-.0118	-.0087	-.0030	-.0120	-.0063	.0006
.40	.40	.20	-.0090	-.0080	-.0045	-.0153	-.0130	-.0062	-.0173	-.0133	-.0037
.45	.40	.15	-.0105	-.0096	-.0063	-.0183	-.0164	-.0099	-.0218	-.0188	-.0090
.50	.40	.10	-.0118	-.0108	-.0084	-.0207	-.0190	-.0140	-.0253	-.0232	-.0151

Table 1. The welfare gap Φ under different policy targets (and $\beta = 0.95$) in the three variants of the model: monopoly rents (Φ^M), R&D firms (Φ^R), and man-made capital (Φ^K: in this case, input shares read $\alpha_1, \alpha_2, \alpha_3$). The welfare gap becomes negative when the resource share (first column) reaches a critical threshold.

5 Remarks

The connections between the present analysis and related literature can be summarized as follows. Mourmouras (1993) uses the basic model of section 2 to show that competition may lead to over-exploitation of privately-owned renewable resources, and describes a set of conservationist policies implementing the Rawlsian optimum. A major difference is the aim of the present analysis: our focus is the existence of situations where agents prefer transfers to laissez-faire for purely selfish reasons, without assuming a predetermined social objective. Second, we have studied individual payoffs in a regime-contingent formulation in order to investigate under what technological and institutional circumstances agents would agree on a higher rate of natural preservation. Third, we have extended the model to include technical progress, monopoly rents, and R&D activity, obtaining insights about the intensity of the welfare effects induced by a higher degree of resource preservation. All the above differences also apply with respect to Krautkraemer and Batina (1999), where the basic model is extended to include a stock-dependent rate of resource regeneration.

In the literature on resource economics, intergenerational transfers are also considered by Howarth (1991) and Gerlagh and Keyzer (2001; 2003). In Howarth (1991), uncertainty about states of nature implies that the Hotelling's rule is not necessarily met, and the competitive equilibrium may thus be inefficient: considering a max-min welfare criterion, Howarth (1991) shows that an optimal scheme of intergenerational transfers allows the economy to obtain intergenerational fairness while restoring efficiency. Gerlagh and Keyzer (2001) consider a production economy where the resource stock has a positive amenity value, and show that a 'trust fund' policy, where future generations receive claims for the natural resource, ensures efficiency and protects the welfare of all generations. In a similar model, Gerlagh and Keyzer (2003) show that conservationist measures may implement optimal allocations that would not be achieved through competitive markets. Apart from substantial differences in the underlying models[16], the common merit of these contributions is to show that fairness

[16]With respect to the present analysis, important differences are represented by uncertainty (which

may be achieved through policies that also preserve efficiency, in line with the view that intergenerational equity and intertemporal efficiency are distinct, and not necessarily conflicting, objectives (Howarth and Norgaard, 1990)).[17] As noted in the Introduction, this view is not challenged by the present analysis, which focuses on the different issue of individual motives for supporting resource-saving policies. In this model, distortionary measures bear an efficiency loss with respect to the first-best policy discussed in Mourmouras (1993) - see sect.3.2. This policy can be easily reinterpreted as an implicit redistribution of property rights across generations operated in each period by fiscal authorities, in line with the main findings of Howarth and Norgaard (1990).

Emphasizing the role of selfish behavior, our analysis is close to the view that intergenerational exchange need not be linked to parental altruism, as recently argued by Boldrin and Rustichini (2000) and Rangel (2003). The general question asked by these authors is: why should present generations invest in assets that are valuable only to future ones? Boldrin and Rustichini (2000) and Rangel (2003) use game-theoretical arguments to show that intergenerational transfers may arise as voting equilibria when dynastic altruism is absent.[18] In particular, Boldrin and Rustichini (2000) show that pay-as-you-go social security can be voted into existence by the majority, because the reduction in current saving implied by taxation raises future returns on capital, thus compensating the negative effect of pension financing. Recalling Proposition 3, our main result hinges on a different mechanism: the reduction in the rate of resource use implied by resource-saving transfers improves production possibilities in the future, and the positive effect on second-period output more than compensates for the negative effect of taxation (provided that resource productivity is sufficiently high).[19]

With respect to models of social security, the opposite direction of transfers in the present analysis (old-to-young) implies substantial differences also from a policymaking perspective, since commitment technologies change. A social security system is supported only if young generations believe that they will receive second-period transfers (Browning, 1975), and this generally requires an *intergenerational commitment device* - i.e. an institutional arrangement that binds generations yet to be born; in the literature on social security, this device takes various forms, such as social contracts (Hammond, 1975; Sjoblom, 1985), reputational mechanisms (Kotlikoff et al. 1988; Cooley and Soares, 1998), or constitutional norms (Azariadis and Galasso, 2002). Resource-saving policies, instead, are supported when young individuals who receive subsidies accept

plays a crucial role in Howarth, 1991) and non-essentiality of the resource for producing output (Gerlagh and Keyzer, 2001). In particular, the fact that natural capital is not essential allows Gerlagh and Keyzer (2001) to consider zero-extraction paths with positive output, a possibility that is ruled out in our model.

[17] Related approaches to fiscal policy with overlapping generations are also considered in the related literature on environmental degradation. In a continuous-time setting, Marini and Scaramozzino (1995) derive the optimal abatement program assuming the Calvo-Obstfeld criterion for intergenerational equity. In a similar model, Bovenberg and Heijdra (1998) show that public debt policy can be used to redistribute in a 'fair' manner across generations the burden of taxation implied by efficient abatement programs.

[18] Rangel (2003) shows that positive expenditures in goods that only benefit the elderly (such as social security) are necessary to achieve an equilibrium with efficient investment in goods that benefit future generations (such as clean environment and education).

[19] Notice that the amplification of the growth effects of transfers, induced by the presence of additional assets in our model, remains different from the interest-rate effect in Boldrin and Rustichini (2000). As shown in sect.4, financial returns are raised by resource-saving policies because of the positive *level effect* on second-period output induced by a reduction in z.

to pay second-period taxes: this requires an *intertemporal commitment device* that binds a given generation in the subsequent period, such as lifetime contracts (sect.3.3). Further differences with respect to the social security literature arise, as already noted (sect.3.4), in the context of sequential voting games due to the particular configuration of payoffs in our model (cf. Proof of Lemma 4).

Due to the first-father problem, enacting permanent transfers involves a paternalistic action at time zero, as no generation would selfishly make the initial gift. As already noted, the logic is similar to Gale (1973), with the major differences that transfers are distortionary and yield welfare gains only if the critical condition is satisfied. Nonetheless, Gale's conclusion can be readapted to the present context as follows: resource-saving transfers begin after the economy

> "has been running along for some time in the [no-transfers] equilibrium, but at time t = 0 some of the old people realize that if they are willing to give up ever so little of their second-period consumption, the economy in the future will move up toward [higher welfare for future generations]. (...) If this altruistic scenario sounds too unrealistic, one can instead imagine a central authority which levies an income tax on the old people in period zero and then sells this income back to the young." (ibid., p.29).

Alternatively, we can imagine a privatization scenario where natural resources previously owned by the State are sold at a lower-than-efficiency price to young generations in period zero, and permanent transfers are then implemented.[20]

6 Conclusions

This paper analyzed the welfare properties of distortionary transfers in a growth model with overlapping generations and privately-owned natural capital. In this framework, unsustainability and resource depletion are a likely outcome of excessive competition, and implementing father-to-son transfers generates a higher degree of resource preservation. Our main result is that all newborn agents prefer intergenerational transfers in both periods of life to persistent laissez-faire conditions, provided that the resource share exceeds a critical threshold level. The reason is that the reduction in the rate of depletion implied by transfers improves production possibilities in the future: if resource productivity is relatively high, the positive effect on second-period output more than compensates (in welfare terms) for the negative effect of taxation. This mechanism is enhanced by the presence of other assets, in addition to natural capital. Extending the model to include man-made capital, monopoly rents and R&D sectors, it is shown that the critical condition becomes less restrictive because the returns from these assets also benefit from the positive growth effect induced by a higher degree of preservation.

The welfare time-path implied by resource-saving policies is not Pareto comparable with that obtained under laissez-faire, because resource owners at time zero suffer a welfare loss due to taxation of the initial stock. The private desire for resource-saving

[20]In this case, the initial selling price (determined by the government) is equivalent to a proportional subsidy to the young at time zero: under balanced budget, the efficiency loss for the public owner would fall again on the first old generation in the form of reduced transfers.

policies unfolds only if agents are either subject to credible pre-commitment, or induced to cooperate with adjacent generations. In the first regard, a succession of lifetime contracts would allow a central authority to implement resource-saving policies in the indefinite future: if young agents are asked to choose between permanent transfers and permanent laissez-faire, the former option is strictly preferred. In a sequential-choice context, the lack of intergenerational cooperation implies that alternative commitment devices must be set, *e.g.* in the form of positive costs of regime-switching. In both cases, agents support resource-saving policies for purely selfish reasons, and a paternalistic action is required at time zero. These two features recall the logic of intergenerational transfers *à la* Gale (1973): if the first resource owner partially renounces his claim over initial endowments, the transmission of this credit forward in time yields welfare gains for all successive generations.

Appendix

A. The basic model

The consumer problem. By (3), (13) and (4), the second-period individual constraint (10) can be rewritten as $e_{t+1} = q_{t+1}(1+\varepsilon)a_t$,which can be substituted in (9) to obtain

$$c_t = w_t - \frac{q_t(1-d_t)e_{t+1}}{q_{t+1}(1+\varepsilon)}. \tag{A1}$$

The individual problem consists of choosing c_t and e_{t+1} in order to maximize lifetime utility subject to (A1): first order conditions for an interior solution imply (14). Substituting equilibrium prices (8)-(7) and condition (14) in individual budget constraints (9) and (10), equilibrium consumption levels are

$$c_t = \frac{w_t}{1+\beta} = \frac{1}{1+\beta}(1-\alpha)y_t, \tag{A2}$$

$$e_{t+1} = \frac{1+n}{1+\beta}(\alpha+\beta)y_{t+1}. \tag{A3}$$

Deriving equation (15). Substituting $e_{t+1} = q_{t+1}(1+\varepsilon)a_t$ in (A3) gives

$$a_t = \frac{(1+n)(\alpha+\beta)}{q_{t+1}(1+\beta)(1+\varepsilon)}y_{t+1}. \tag{A4}$$

From (7) and (13), $q_{t+1} = \alpha m_{t+1}^{\alpha} x_{t+1}^{\alpha-1}(1-\tau_{t+1})$ can be substituted in (A4) to obtain

$$a_t = \frac{(1+n)(\alpha+\beta)}{\alpha(1+\beta)(1+\varepsilon)(1-\tau_{t+1})}x_{t+1}. \tag{A5}$$

Now consider the system

$$\frac{q_{t+1}}{q_t} = \frac{e_{t+1}(1-d_t)}{\beta c_t(1+\varepsilon)}, \tag{A6}$$

$$\frac{q_{t+1}}{q_t} = \frac{p_{t+1}}{p_t}\left(\frac{1-\tau_{t+1}}{1-\tau_t}\right), \tag{A7}$$

where (A6) is the optimality condition (14), and (A7) is implied by no-arbitrage condition (13). Substituting (A2)-(A3) in (A6), and (7) in (A7) respectively gives

$$\frac{q_{t+1}}{q_t} = \frac{(1+n)(\alpha+\beta)(1-d_t)}{\beta(1-\alpha)(1+\varepsilon)}\left(\frac{y_{t+1}}{y_t}\right), \tag{A8}$$

$$\frac{q_{t+1}}{q_t} = \frac{x_t}{x_{t+1}}\left(\frac{1-\tau_{t+1}}{1-\tau_t}\right)\frac{y_{t+1}}{y_t}, \tag{A9}$$

implying

$$\frac{x_{t+1}}{x_t} = \frac{\beta(1-\alpha)(1+\varepsilon)(1-\tau_{t+1})}{(1+n)(\alpha+\beta)(1-d_t)(1-\tau_t)}. \tag{A10}$$

Substituting (A10) in (A5) gives eq.(15) in the text.

Proof of Proposition 1. Under laissez-faire $z_{t+1} = z_t = \tilde{z}$, which implies that U_t is proportional to y_t (see equation (A14) derived below). Hence, satisfying the sustainability condition (1) in the laissez-faire economy requires $\theta^y \geq 1$. Setting $z_{t+1} = z_t = \tilde{z}$ in (18) it follows that $\theta^y \geq 1$ if and only if (22) is satisfied. Substituting (15) and $\gamma = \beta^{-1} - 1$ in (22) yields (23).

Deriving tax-subsidy rates in (25). Setting $z_t = z'$, $\tau_t = \tau'$ and $d_t = d'$ in equations (24) and (11) gives

$$z' = \tilde{z}\left(1-\tau'\right)\left(1-d'\right), \tag{A11}$$

$$\tau' z' = \left(1-\tau'\right)d', \tag{A12}$$

respectively. Substituting (A12) in (A11) gives $\tau' = \frac{d'}{\tilde{z}(1-d')}$, which can be substituted back in (A11) to obtain $d' = \frac{\tilde{z}-z'}{1+\tilde{z}}$, which is the subsidy rate level in (25). The tax rate level in (25) then follows from $\tau' = \frac{d'}{\tilde{z}(1-d')}$ as obtained above.

Proof of Lemma 2. It follows from (A2)-(A3) that

$$U_t = \log\left(\frac{1-\alpha}{1+\beta}\right) + \beta\log(1+n)\frac{\alpha+\beta}{1+\beta} + \log y_t + \beta\log y_{t+1}. \tag{A13}$$

By (18), $\beta\log y_{t+1} = \beta\log y_t + \alpha\beta\log\frac{z_{t+1}(1+\rho)}{z_t(1+z_{t+1})}$, and (A13) can be rewritten as

$$U_t = \log\left\{\left(\frac{1-\alpha}{1+\beta}\right)\left[\frac{(1+n)(\alpha+\beta)}{1+\beta}\right]^{\beta}\left[\frac{z_{t+1}(1+\rho)}{z_t(1+z_{t+1})}\right]^{\alpha\beta} y_t^{1+\beta}\right\}. \tag{A14}$$

If the policymaker sets $z_t = \rho$ in each period, (18) implies y_t be constant over time and (A14) implies U_t be constant over time. More generally, from (A14), any path with constant utility requires

$$\frac{z_{t+2}}{1+z_{t+2}} = \frac{z_{t+1}}{(1+\rho)}\left[\frac{z_t(1+z_{t+1})}{z_{t+1}(1+\rho)}\right]^{\frac{1}{\beta}} \quad \text{for each } t \in [0,\infty). \tag{A15}$$

Deriving expression (28). Given the initial endowment $R_0 \equiv r_0 N_0$, solving (16) and (17) backward yields

$$x_t = r_0\left(\frac{1+\varepsilon}{1+n}\right)^t \cdot \frac{z_t}{1+z_t}\prod_{j=0}^{t-1}\frac{1}{1+z_j}. \tag{A16}$$

Substituting (A16) in $y_t = m_t^{\alpha} x_t^{\alpha}$ gives

$$y_t = \left(\frac{z_t}{1+z_t} \phi_t \right)^{\alpha}, \tag{A17}$$

where

$$\phi_t \equiv \frac{r_0 m_0 (1+\rho)^t}{\prod_{j=0}^{t-1} (1+z_j)} \tag{A18}$$

is a function of H_t and is therefore taken as given by the agent born in period t. Expression (A18) implies that $\phi_{t+1} = \phi_t (1+\rho)(1+z_t)^{-1}$, thus

$$y_{t+1} = \left[\frac{(1+\rho) z_{t+1}}{(1+z_t)(1+z_{t+1})} \phi_t \right]^{\alpha}. \tag{A19}$$

Substituting (A17) and (A19) in (A13) yields

$$U_t = \log \left\{ \left[\left(\frac{1-\alpha}{1+\beta} \right) \left(\frac{z_t}{1+z_t} \phi_t \right) \right]^{\alpha} \left[\frac{(1+n)(\alpha+\beta)}{1+\beta} \right]^{\beta} \left[\frac{(1+\rho) z_{t+1}}{(1+z_t)(1+z_{t+1})} \phi_t \right]^{\alpha\beta} \right\}.$$

Setting $\Omega_t \equiv \log \left\{ \left(\frac{1-\alpha}{1+\beta} \right) \phi_t^{\alpha} \left[\frac{(1+n)(\alpha+\beta)}{1+\beta} \phi_t^{\alpha} \right]^{\beta} \right\}$ yields expression (28) in the text.

Deriving expressions (29) and (30). It follows from (28) that

$$V(0,0) = \Omega + \log \left\{ \left(\frac{\tilde{z}}{1+\tilde{z}} \right)^{\alpha} \left(\frac{1}{1+\tilde{z}} \right)^{\alpha\beta} \left[\frac{(1+\rho)\tilde{z}}{1+\tilde{z}} \right]^{\alpha\beta} \right\}, \tag{A20}$$

$$V(0,1) = \Omega + \log \left\{ \left(\frac{\tilde{z}}{1+\tilde{z}} \right)^{\alpha} \left(\frac{1}{1+\tilde{z}} \right)^{\alpha\beta} \left[\frac{(1+\rho) z'}{1+z'} \right]^{\alpha\beta} \right\}, \tag{A21}$$

$$V(1,0) = \Omega + \log \left\{ \left(\frac{z'}{1+z'} \right)^{\alpha} \left(\frac{1}{1+z'} \right)^{\alpha\beta} \left[\frac{(1+\rho)\tilde{z}}{1+\tilde{z}} \right]^{\alpha\beta} \right\}, \tag{A22}$$

$$V(1,1) = \Omega + \log \left\{ \left(\frac{z'}{1+z'} \right)^{\alpha} \left(\frac{1}{1+z'} \right)^{\alpha\beta} \left[\frac{(1+\rho) z'}{1+z'} \right]^{\alpha\beta} \right\}. \tag{A23}$$

Expressions (29) and (30) in the text are proved as follows: $\tilde{z} > z'$ implies

$$\frac{z'}{\tilde{z}} \left(\frac{1+\tilde{z}}{1+z'} \right) < 1. \tag{A24}$$

Hence, from (A20)-(A21) we have $V(0,0) > V(0,1)$, because $\left[\frac{\tilde{z}(1+z')}{z'(1+\tilde{z})} \right]^{\alpha} > 1$; from (A22)-(A23) we have $V(1,0) > V(1,1)$, because $\left[\frac{\tilde{z}(1+z')}{z'(1+\tilde{z})} \right]^{\alpha\beta} > 1$.

Proof of Proposition 3. By (A20) and (A23), $V(0,0) < V(1,1)$ if and only if

$$\left(\frac{\tilde{z}}{1+\tilde{z}} \right)^{\alpha(1+\beta)} \left(\frac{1}{1+\tilde{z}} \right)^{\alpha\beta} < \left(\frac{z'}{1+z'} \right)^{\alpha(1+\beta)} \left(\frac{1}{1+z'} \right)^{\alpha\beta}.$$

Substituting $1+\tilde{z} = \frac{\beta+\alpha}{\beta(1-\alpha)}$, this inequality reduces to (32). It follows from (29) and (30) that if (32) is satisfied the only possible payoff ranking is (31).

Deriving expression (33). From (A20) and (A23), the gap $\Phi = V(0,0) - V(1,1)$ equals

$$\Phi = \log \left\{ \left(\frac{\tilde{z}}{z'} \right)^{\alpha+\alpha\beta} \left(\frac{1+z'}{1+\tilde{z}} \right)^{\alpha+2\alpha\beta} \right\}.$$

Substituting $z' = \mu\tilde{z}$ and eq.(15) in the above expression yields equation (33) in the text.

The Rawls-optimal path. Along a Rawls-optimal path, (i) utility per capita must be constant through generations born in any $t \geq 0$ and (ii) the constant utility level must be the maximum that can be sustained indefinitely. As regards the first point, utility per capita is constant through generations if $y_t = y^*$ at any $t \geq 0$, implying $m_t^\alpha x_t^\alpha = y^*$. Defining $\tilde{x}_t \equiv m_t x_t$, the Rawls-optimal path requires $\tilde{x}_t = \tilde{x}^* = (y^*)^{\frac{1}{\alpha}}$ constant. Multiplying by m_t the resource constraint $r_{t+1}(1+n) = (1+\varepsilon)(r_t - x_t)$, and defining $\tilde{r}_t \equiv r_t m_t$ we obtain

$$\tilde{r}_{t+1} = (1+\rho)(\tilde{r}_t - \tilde{x}^*). \tag{A25}$$

Equation (A25) displays a unique steady-state point,

$$\tilde{r}^* = \frac{1+\rho}{\rho}\tilde{x}^*. \tag{A26}$$

Since $\rho > 0$, this equilibrium is unstable. As a consequence, if $\tilde{x}^* > \tilde{r}_0 \frac{\rho}{1+\rho}$ then $\tilde{r}_t$ diverges to minus infinity: in this case, the Rawlsian path is unfeasible since the resource stock becomes negative in finite time. If set $\tilde{x}^* < \tilde{r}_0 \frac{\rho}{1+\rho}$ then $\tilde{r}_t$ diverge to plus infinity, which is feasible but technologically inefficient, since there would be waste of productive resources. As a consequence, the Rawls-optimal plan is to chose $\tilde{x}^* = \frac{\rho}{1+\rho}\tilde{r}_0$, which implies $x_0^* = \frac{\rho}{1+\rho}r_0$. Since x_t^* must decline geometrically at rate δ to ensure constancy of $\tilde{x}^*$, natural capital and the resource stock evolve according to (34) along a Rawls-optimal path, and output per capita is $y^* = \left(\frac{\rho}{1+\rho} m_0 r_0 \right)^\alpha$ at each $t \geq 0$. Given y^*, lifetime utility is maximized by consumption bundles c^* and e^* satisfying

$$(c^*, e^*) = \arg\max \left\{ \log c^* + \beta \log e^* \text{ sub } y^* = c^* + e^* (1+n)^{-1} \right\}.$$

Assuming an interior solution, the first-order condition $e^* = \beta c^* (1+n)$ and the aggregate constraint imply conditions (35).

First-best policy. The first-best policy is the same described in Mourmouras (1993). At time zero, the resource stock is expropriated and a stock J_0 of fiat currency is introduced in the economy as a lump-sum transfer to the initial old. Denoting the quantity of money per young individual as $j_t = J_0/N_t$, the first father receives (and consumes)

$$\frac{j_t(1+n)}{p_t^y} = e_0,$$

where p_t^y is the price index of the economy. All successive generations face individual constraints

$$c_t = w_t + s_t - (j_t/p_t^y), \tag{A27}$$

$$e_{t+1} = (j_t/p_{t+1}^y) \tag{A28}$$

where s_t is the lump-sum subsidy through which the government transfers all rents from natural capital to the currently young. Hence, consumers maximize U_t subject to (A27)-(A28), obtaining first-order conditions

$$e_{t+1} = \beta c_t \left(p_t^y / p_{t+1}^y \right). \tag{A29}$$

Since the government is implementing the depletion path described in (34), transfers to the young equal $s_t = \alpha y^*$ in each period: substituting this amount in the budget constraints (A27)-(A28) together with the first-order condition (A29), we obtain

$$\begin{aligned} c_t &= (1+\beta)^{-1} y^* = c^*, \\ e_t &= \beta (1+n)(1+\beta)^{-1} y^* = e^*, \end{aligned}$$

which coincides with the Rawls-optimal allocation (35).

Proof of Lemma 4. A history-dependent strategy for the representative agent born at the beginning of period t is denoted by $\sigma_t(H_t)$, mapping previous generations' actions into the choice space $\{0,1\}$. In this case, $\sigma_t(H_t)$ becomes part of the history set affecting subsequent strategies, $\sigma_{t+1}(H_{t+1}) = \sigma_{t+1}(H_t, \sigma_t(H_t))$. A subgame perfect equilibrium is a sequence of strategies $(\sigma_t)_{t=0}^{\infty}$ if and only if, for every t and every history H_t, strategy $\sigma_t(H_t)$ yields an expected lifetime payoff exceeding that yielded by the opposite strategy $\bar{\sigma}_t(H_t)$, i.e.

$$V_t(\sigma_t(H_t), \sigma_{t+1}(H_t, \sigma_t(H_t))) > V_t(\bar{\sigma}_t(H_t), \sigma_{t+1}(H_t, \bar{\sigma}_t(H_t))). \tag{A30}$$

Now assume that (32) holds, so that (31) holds. If $\sigma_t(H_t) = 0$, it is impossible to satisfy both (A30) and (31) since, by (31), all possible payoffs with $\sigma_t(H_t) = 0$ are always lower than all alternative payoffs with $\bar{\sigma}_t(H_t) = 1$. Hence, when (32) holds, $\sigma_t(H_t) = 0$ cannot be part of a subgame perfect equilibrium sequence (and, by extension, laissez-faire will not arise as an equilibrium outcome with growing population). This result is due to the fact that, in (31), $V(1,0)$ and $V(1,1)$ are strictly preferred to laissez-faire conditions in the first period. Pension games are different in that the relevant payoff is of the type (cf. Boldrin and Rustichini, 2000: eq.3.5)

$$\tilde{V}(0,1') > \tilde{V}(1',1') > \tilde{V}(0,0) > \tilde{V}(1',0) \tag{A31}$$

where $1'$ means young-to-old transfers. In this case, laissez-faire outcomes may be part of a subgame perfect equilibrium sequence since it is possible to set $\sigma_t(H_t) = 0$ while satisfying both ranking (A31) and the equilibrium condition (A30) - see Boldrin and Rustichini (2000: p.51).

Proof of Lemma 5. When condition (32) holds, payoffs are ranked as in (31). Hence, for any history $(\eta_0, \eta_1, ...)$, the dominant strategy for young agents is to vote for transfers, whereas each old in period t has incentives to vote laissez-faire for any η_{t-1}. Hence, qualified majorities never arise, implying $\eta_t = \eta_0$ for all $t > 0$.

Proof of Lemma 6. From (40), we have $\bar{V}_t(1,1) - \bar{V}_t(0,0) = V_t(1,1) - V_t(0,0) - \epsilon_t(1)$. Substituting $\Phi \equiv V_t(1,1) - V_t(0,0)$, it follows that $\bar{V}_t(1,1) > \bar{V}_t(0,0)$ if (41) is satisfied. On the other hand, (40) implies that $\bar{V}_t(1,1) > \bar{V}_t(1,0)$ if $\beta\epsilon_{t+1}(1) > V_t(1,0) - V_t(1,1)$, which - from (A22) and (A23) - can be rewritten as

$$\beta\epsilon_{t+1}(1) > \log\left[\frac{\tilde{z}}{z'}\left(\frac{1+z'}{1+\tilde{z}}\right)\right]^{\alpha\beta}. \tag{A32}$$

Substituting $z' = \mu\tilde{z}$ and rearranging terms yields (42). This reasoning implies that if (41)-(42) hold at t we have $\bar{V}_t(1,1) > \bar{V}_t(1,0)$ and $\bar{V}_t(1,1) > \bar{V}_t(0,0)$. From (40), it also derives that $\bar{V}_t(1,1) > \bar{V}_t(0,1)$. As a consequence, if (41)-(42) hold, the highest lifetime payoff for young agents in period t is $\bar{V}_t(1,1)$, and the dominant strategy in the political game is to vote for transfers in both periods of life. By sequential reasoning, if $\eta_0 = 1$ and the above conditions always hold, transfers receive unanimous political support from all generations born in $t \geq 0$.

B. The model with capital

Deriving expression (50). As shown in Mourmouras (1993: p.264), the natural capital-resource ratio is constant in the laissez-faire economy with capital. From the government budget constraint (11), constant tax-subsidy rates imply $z_t = z$ constant as well. From the individual budget constraint (44),

$$q_t a_t (1-d) + k_{t+1} = w_t - c_t = \frac{\alpha_2 \beta}{1+\beta} y_t, \tag{A33}$$

where we have used $w_t = \alpha_2 y_t$ and $c_t = w_t (1+\beta)^{-1}$. Using the equilibrium condition $q_t = p_t (1-\tau)$ and the profit-maximizing condition $p_t = \alpha_1 (y_t/x_t)$, we can rewrite net expenditure in resource assets as

$$q_t a_t (1-d) = \frac{\alpha_1 (1-\tau)(1-d)}{z_t} y_t, \tag{A34}$$

and substitute in (A33) to obtain

$$\frac{k_{t+1}}{y_t} = \frac{\alpha_2 \beta}{1+\beta} - \frac{\alpha_1 (1-\tau)(1-d)}{z_t}. \tag{A35}$$

Substituting the profit-maximizing condition $i^k_{t+1} = \alpha_3 (y_{t+1}/k_{t+1})$ in the Hotelling rule $i^k_{t+1} = \frac{q_{t+1}}{q_t}\left(\frac{1+\varepsilon}{1-d_t}\right)$, and using the equilibrium condition $q_t = p_t(1-\tau)$ and the profit-maximizing condition $p_t = \alpha_1 (y_t/x_t)$, we obtain

$$\frac{k_{t+1}}{y_t} = \alpha_3 \left(\frac{x_{t+1}}{x_t}\right)\left(\frac{1-d}{1+\varepsilon}\right). \tag{A36}$$

Plugging (A36) in (A35) and using $x_{t+1}(1+z) = x_t(1+\varepsilon)$, we obtain expression (50) in the text.

Deriving expressions (53) and (54). From (51) we have

$$\theta^k_{t+1} = \theta^y_t = (\theta^x_t)^{\alpha_1}\left(\theta^k_t\right)^{\alpha_3}, \tag{A37}$$

which can be log-linearized as (defining $\bar{\theta}^i_t \equiv \log \theta^i_t$)

$$\bar{\theta}^k_{t+1} = \alpha_1 \bar{\theta}^x_t + \alpha_3 \bar{\theta}^k_t = \alpha_3 \bar{\theta}^k_t + \alpha_1 \log\left[(1+\varepsilon)/(1+z)\right]. \tag{A38}$$

Since $\alpha_3 < 1$, $\bar{\theta}^k_t$ converges to the unique steady state

$$\bar{\theta}^k = \frac{\alpha_1}{1-\alpha_3} \log\left[(1+\varepsilon)/(1+z)\right].$$

As a consequence,

$$\lim_{t\to\infty}\theta_t^k = [(1+\varepsilon)/(1+z)]^{\frac{\alpha_1}{1-\alpha_3}}. \tag{A39}$$

From (A37), it derives that $\lim_{t\to\infty}\theta_t^k = \lim_{t\to\infty}\theta_t^y$, which proves expression (53). As regards the interest factor, we have

$$\lim_{t\to\infty} i_t = \lim_{t\to\infty}\alpha_3(y_t/k_t) = (1+z)\lim_{t\to\infty}\theta_t^y,$$

which yields (54) after substitution of (53).

The critical condition (55). Using $c_t = \alpha_2(1+\beta)^{-1}y_t$ and $e_{t+1} = i_{t+1}\beta c_t = \frac{\alpha_2\alpha_3\beta}{1+\beta}\left(\frac{y_t}{k_{t+1}}\right)y_{t+1}$, lifetime utility of agents born in t equals

$$U_t = \log\left(\frac{\alpha_2}{1+\beta}y_t\right) + \beta\log\left[\frac{y_t}{k_{t+1}}\left(\frac{\alpha_3\alpha_2\beta}{1+\beta}\right)y_{t+1}\right]. \tag{A40}$$

Setting $e_{t+1} = i_{t+1}\beta c_t = \frac{\alpha_2\alpha_3\beta}{1+\beta}\left(\frac{y_t}{k_{t+1}}\right)y_{t+1}$ in period t and substituting in the aggregate constraint (46) yields $k_{t+1} = \bar{\varphi}_t y_t$, where

$$\bar{\varphi}_t \equiv 1 - \frac{\alpha_2}{1+\beta} - \frac{\alpha_2\alpha_3\beta}{1+\beta}\left(\frac{y_{t-1}}{k_t}\right)$$

is taken as given by agents born in period t. Hence, (A40) can be rewritten as

$$U_t = \log\left\{\frac{\alpha_2}{1+\beta}\left[\frac{\alpha_3\alpha_2\beta}{\bar{\varphi}_t(1+\beta)}\right]^\beta\right\} + \log y_t + \beta\log y_{t+1}. \tag{A41}$$

Using the definition of ϕ_t in (A18), output at subsequent dates can be written as[21]

$$y_t = \left(\frac{z_t}{1+z_t}\right)^{\alpha_1}\phi_t^{\alpha_1}k_t^{\alpha_3}, \tag{A42}$$

$$y_{t+1} = \left(\frac{z_t(1+\varepsilon)}{(1+z_t)(1+z_{t+1})}\right)^{\alpha_1}\phi_t^{\alpha_1}\bar{\varphi}_t^{\alpha_3}y_t^{\alpha_3}. \tag{A43}$$

where we have used $k_{t+1}^{\alpha_3} = (\bar{\varphi}_t y_t)^{\alpha_3}$. Substituting (87)-(87) in (A41),

$$U_t = \Omega_t' + \log\left\{\left(\frac{z_t}{1+z_t}\right)^{\alpha_1}\left[\frac{1+\varepsilon}{1+z_{t+1}}\left(\frac{z_t}{1+z_t}\right)^{(1+\alpha_3)}\right]^{\alpha_1\beta}\right\}, \tag{A44}$$

where we have defined

$$\Omega_t' \equiv \log\left[\frac{\alpha_2\phi_t^{\alpha_1}k_t^{\alpha_3}}{1+\beta}\left(\frac{\alpha_3\alpha_2\beta\phi_t^{\alpha_1(1+\alpha_3)}\varphi_t^{\alpha_3}k_t^{\alpha_3^2}}{\bar{\varphi}_t(1+\beta)}\right)^\beta\right]. \tag{A45}$$

Since Ω_t' is taken as given by agents born in t, the gap between utility under life-persistent transfers ($z_t = z_{t+1} = z'$) and under laissez-faire ($z_t = z_{t+1} = \tilde{z}$) is given by

$$\Phi = V(0,0) - V(1,1) = \log\left\{\left[\frac{\tilde{z}}{z'}\left(\frac{1+z'}{1+\tilde{z}}\right)\right]^{\alpha_1+\alpha_1\beta(1+\alpha_3)}\left(\frac{1+z'}{1+\tilde{z}}\right)^{\alpha_1\beta}\right\}. \tag{A46}$$

From (A46), setting $z' = \mu\tilde{z}$, the condition for $\Phi < 0$ is given by inequality (55) in the text.

[21] With $\delta = n = 0$, ϕ in (A18) is here simplified by $\rho = \varepsilon$ and $m_0 = 1$).

C. The model with monopoly rents

Deriving equation (62). Since (56) displays constant returns to scale, profit maximization of final output producers implies

$$y_t = p_t x_t + w_t + \nu_3^{-1} g b_t = p_t x_t + [c_t + q_t a_t (1-d) + f_t] + \nu_3^{-1} g b_t,$$

where the term in square brackets follows from (60). Setting (61) at time t and substituting for $q_t a_t$ yields

$$y_t = c_t + e_t - g\pi_t + \nu_3^{-1} g b_t,$$

where we have simplified $p_t x_t \tau = q_t a_t d$ from the government budget constraint (11). Substituting monopoly rents from (58) yields (62).

Deriving expression (65). Substituting $c_t = \nu_2 (1+\beta)^{-1}$ and $g b_t = \nu_3^2 y_t$ in the aggregate constraint (62) yields

$$e_{t+1} = \left[\left(1-\nu_3^2\right)(1+\beta) - \nu_2\right](1+\beta)^{-1} y_{t+1}. \tag{A47}$$

Substituting (A47) in the Euler condition $e_{t+1} = i^f_{t+1} \beta c_t$, and using the Hotelling rule (63) we get

$$\frac{x_{t+1}}{x_t} = \frac{\nu_2 \beta (1+\varepsilon)(1-d)^{-1}}{\left(1-\nu_3^2\right)(1+\beta) - \nu_2}, \tag{A48}$$

which implies that z_t is constant over time (knife-edge equilibrium). Substituting $\theta^x = (1+\varepsilon)(1+z)^{-1}$ yields expression (65).

Deriving the gap function (67). Substituting $c_t = \nu_2 (1+\beta)^{-1}$ and (A47) in the utility function gives

$$U_t = \log\left\{\frac{\nu_2}{1+\beta}\left[\frac{\left(1-\nu_3^2\right)(1+\beta)-\nu_2}{1+\beta}\right]^\beta\right\} + \log\left[y_t^{1+\beta}\left(\frac{1+\varepsilon}{1+z}\right)^{\frac{\nu_1 \beta}{1-\nu_3}}\right] \tag{A49}$$

where we have substituted $y_{t+1} = y_t \left[(1+\varepsilon)/(1+z)\right]^{\frac{\nu_1}{1-\nu_3}}$ from (66). Substituting the resource constraint $x_t = r_t z (1+z)^{-1}$ and the equilibrium condition $b_t = \left(\nu_3^2 x_t^{\nu_1}\right)^{\frac{1}{1-\nu_3}}$ in the production function $y_t = x_t^{\nu_1} g b_t^{\nu_3}$ yields

$$y_t = \frac{1}{\nu_3^2} g_t \left(\nu_3^2 r_t^{\nu_1}\right)^{\frac{1}{1-\nu_3}} \left(\frac{z}{1+z}\right)^{\frac{\nu_1}{1-\nu_3}}, \tag{A50}$$

where r_t is taken as given by agents born in t. Hence, substituting (A50) in (A49) and defining

$$\Omega''_t \equiv \log\left\{\frac{\nu_2}{1+\beta}\left[\frac{\left(1-\nu_3^2\right)(1+\beta)-\nu_2}{1+\beta}\right]^\beta \left(\frac{1}{\nu_3^2} g \left(\nu_3^2 r_t^{\nu_1}\right)^{\frac{1}{1-\nu_3}}\right)^{1+\beta}\right\},$$

we obtain

$$U_t = \Omega''_t + \log\left[\left(\frac{z}{1+z}\right)^{\frac{\nu_1(1+\beta)}{1-\nu_3}} \left(\frac{1+\varepsilon}{1+z}\right)^{\frac{\nu_1 \beta}{1-\nu_3}}\right]. \tag{A51}$$

Setting $z = z'$ for $V(1,1)$ and $z = \tilde{z}$ for $V(0,0)$, the gap function is $\Phi = V(0,0) - V(1,1)$ can be expressed as in (67), where $\mu \equiv z'/\tilde{z}$ as usual.

D. The model with R&D

Deriving equation (80). Since (68) displays constant returns to scale, profit maximization of final output producers implies

$$y_t = p_t x_t + w_t + \nu_3^{-1} g_t b_t = p_t x_t + [c_t + q_t a_t (1-d) + f_t + h_t] + \nu_3^{-1} g_t b_t,$$

where the term in square brackets follows from (75). Setting (76) at time t and substituting for $q_t a_t$ yields

$$y_t = c_t + e_t + h_t - g_t \pi_t + \nu_3^{-1} g_t b_t,$$

where we have simplified $p_t x_t \tau = q_t a_t d$ from (11). Substituting monopoly profits $\pi_t = \nu_3^{-1}(1-\nu_3) b_t$ yields (80).

Derivation of system (82)-(83). Substituting (74), (77) and $\pi_{t+1} = \nu_3^{-1}(1-\nu_3) b_{t+1}$ in (79) we obtain

$$i_{t+1}^h = \frac{(g_{t+1} - g_t)(\pi_{t+1} + v_{t+1})}{h_t} = \xi_t \left[\nu_3^{-1}(1-\nu_3) b_{t+1} + \xi_{t+1}^{-1}\right].$$

Substituting (73) and recalling that $y_t = \nu_3^{-2} g_t b_t$,

$$i_{t+1}^h = [1 + \psi\nu_3(1-\nu_3)]\, \theta_{t+1}^b = [1 + \psi\nu_3(1-\nu_3)] \left(\theta_{t+1}^x\right)^{\frac{\nu_1}{1-\nu_3}}, \tag{A52}$$

where we have used (71). Now rewrite the Hotelling rule (81) as

$$i_{t+1}^h = (1+\varepsilon)\, \theta_{t+1}^y \left[(1-d)\, \theta_{t+1}^x\right]^{-1}. \tag{A53}$$

Plugging (A53) in (A52) and using $\theta_{t+1}^y = \theta_{t+1}^b \theta_{t+1}^g$, we get

$$\theta_{t+1}^x = \left(\frac{1+\varepsilon}{1-d}\right) \left[\frac{1 + \psi(h_t/y_t)}{1 + \psi\nu_3(1-\nu_3)}\right], \tag{A54}$$

where we have substituted $\theta_{t+1}^g = [1 + \psi(h_t/y_t)]$ from (72) and (73). The only endogenous variable in (A54) is the marginal propensity to invest in R&D, h_t/y_t, which can be obtained as follows. Rewrite (75) as

$$c_t/y_t = w_t - \nu_1(1-d)(1-\tau) z_t^{-1} - g_t v_t - (h_t/y_t),$$

and substitute $c_t = w_t (1+\beta)^{-1}$ and (74) to obtain

$$h_t/y_t = \nu_2 \beta (1+\beta)^{-1} - \psi^{-1} - \nu_1 (1-d)(1-\tau) z_t^{-1}. \tag{A55}$$

which is equivalent to expression (83) in the text. Note that the marginal propensity to invest in existing firms, $f_t v_t = 1/\psi$, must be less than unity in an interior equilibrium, so that positive R&D activity requires $\psi > 1$ as claimed in footnote 14. From (A54) and (A55), the growth rate of natural capital solely depends on z_t, which is therefore constant and obtained recursively: setting $\theta_{t+1}^x = (1+\varepsilon)(1+z)^{-1}$ in (A54) yields (82), to be combined with (A55) as shown in the main text.

The critical condition (86). From $e_{t+1} = \beta c_t i_{t+1}^h$ and $c_t = w_t (1+\beta)^{-1}$, lifetime utility equals

$$U_t = \log\left[c_t^{1+\beta} \beta^\beta \left(i_{t+1}^h\right)^\beta\right] = \log\left\{\left[\nu_2 (1+\beta)^{-1} y_t\right]^{1+\beta} \beta^\beta \left(i_{t+1}^h\right)^\beta\right\}.$$

Substituting (A52) and $\theta^x = (1+\varepsilon)(1+z)^{-1}$,

$$U_t = \log \left\{ \beta^\beta \left[1 + \psi \nu_3 (1-\nu_3)\right]^\beta \left(\frac{\nu_2}{1+\beta} \right)^{1+\beta} \left(\frac{1+\varepsilon}{1+z} \right)^{\frac{\nu_1 \beta}{1-\nu_3}} y_t^{1+\beta} \right\}. \quad \text{(A56)}$$

Substituting $x_t = r_t z (1+z)^{-1}$ in (70), output reads

$$y_t = g_t x_t^{\nu_1} b_t^{\nu_3} = \nu_3^{\frac{2\nu_3}{1-\nu_3}} g_t x_t^{\frac{\nu_1}{1-\nu_3}} = g_t r_t^{\frac{\nu_1}{1-\nu_3}} \nu_3^{\frac{2\nu_3}{1-\nu_3}} \left(\frac{z}{1+z} \right)^{\frac{\nu_1}{1-\nu_3}}. \quad \text{(A57)}$$

Plugging (A57) in (A56) yields

$$U_t = \Omega_t''' + \log \left[\left(\frac{1+\varepsilon}{1+z} \right)^{\frac{\nu_1 \beta}{1-\nu_3}} \left(\frac{z}{1+z} \right)^{\frac{\nu_1}{1-\nu_3}(1+\beta)} \right], \quad \text{(A58)}$$

where we have defined

$$\Omega_t''' \equiv \log \left\{ \beta^\beta \left[1 + \psi \nu_3 (1-\nu_3)\right]^\beta \left(\nu_2 (1+\beta)^{-1} g_t r_t^{\frac{\nu_1}{1-\nu_3}} \nu_3^{\frac{2\nu_3}{1-\nu_3}} \right)^{1+\beta} \right\},$$

which is historically-determined and taken as given by agents born in t. Hence, the welfare gap is

$$\Phi = V(0,0) - V(1,1) = \log \left[\left(\frac{\tilde{z}}{z'} \right)^{\frac{\nu_1}{1-\nu_3}(1+\beta)} \left(\frac{1+z'}{1+\tilde{z}} \right)^{(1+2\beta)\frac{\nu_1}{1-\nu_3}} \right]. \quad \text{(A59)}$$

Setting $\mu = z'/\tilde{z}$, it follows from (A59) that $\Phi < 0$ when inequality (86) holds.

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