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Simone Valente

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Abstract

This paper studies an endogenous growth model with human capital, exhaustible resources, and overlapping generations. Under laissez-faire, higher study time reduces depletion rates by increasing the share of resources that present generations are willing to sell to successors. However, selfish behavior may prevent competitive sustained growth, and implementing utilitarian allocations generally induces optimal-and-sustainable paths. It is shown that: (i) raising study time and decreasing resource depletion are always complementary targets in optimal policies; (ii) growth effects are stronger the lower the optimal share of exploited resources; (iii) generational welfare gains from optimal policies are delayed by faster depletion and, contrary to intuition, anticipated by lower social discount rates.

Keywords Endogenous Growth, Exhaustible Resources, Human Capital, Overlapping Generations, Intergenerational Fairness, Sustainability.

JEL Codes O11, J24, Q32

Dr. Simone Valente
CER-ETH Zurich
Zurichbergstrasse 18, ZUE-F15
CH-8032 Zurich (Switzerland)

1 Introduction

Overcoming the constraints set by depletable essential inputs, such as oil, is a major challenge facing modern economies. When production possibilities are limited by resource scarcity, achieving sustained economic growth is a matter of both technological development and intertemporal distribution of resources. Non-declining welfare typically requires that production possibilities are being enhanced over time by some form of technical change. But the ability to produce a constant flow of output does not suffice ensuring that future generations' welfare is preserved: the accumulation process of the various productive stocks is determined by intertemporal rules that may, or may not be compatible with intergenerational fairness. The modern literature on the sustainability of economic growth has been confronted with this two-sided problem since the seminal works of Dasgupta and Heal (1974) and Solow (1974), and the same dichotomy can still be found in the approaches followed by recent contributions on sustainability.[1]

A first strand of literature focuses on the role of technological change, and I will label it as '*sustained growth literature*'. Following the main insights of Stiglitz (1974), several contributions reformulated the problem of obtaining non-declining consumption in the context of endogenous growth theories. In the new framework, the conditions for achieving positive growth rates are intimately linked to the development of innovations and the profitability of R&D investment (Barbier, 1999; Sholz and Ziemes, 1999; Groth and Schou, 2002; Grimaud and Rougé, 2003). When production is heavily dependent on the use of exhaustible resources, endogenous technical progress may guarantee sustained consumption in the long run: the general condition is that the rate of resource-augmenting technical progress must not fall below the utility discount rate.[2] This result clearly hinges on the validity of the Keynes-Ramsey rule. Indeed, these contributions assume that saving decisions are taken by utility-maximizing consumers with infinite lifetimes, and intertemporal allocations are biased in favor of early-in-time consumption due to discounting.

A parallel body of contributions, which I label as '*sustainable development literature*', analyzes the conditions for preserving the welfare of future generations

[1] In the neoclassical growth model, it is possible to produce a constant flow of output if the relative production share of reproducible capital goods is greater than that of exhaustible natural inputs (Solow, 1974). However, if savings are governed by the Keynes-Ramsey rule, consumption per capita must decline in the long run for any positive discount rate (Dasgupta and Heal, 1974).

[2] This result holds even in the presence of poor substitution possibilities between natural capital and other inputs (Bretschger and Smulders, 2006), but requires that technical change be, implicitly or explicitly, of the resource-augmenting type (Di Maria and Valente, 2006).

assuming explicit demographic structures - in particular, overlapping generations models with selfish agents.[3] These contributions emphasized the fact that intergenerational equity and intertemporal efficiency are distinct objectives (Howarth and Norgaard, 1992; Mourmouras, 1993): once that welfare criteria incorporate fairness concerns, efficiency *per se* does not guarantee socially optimal outcomes, and achieving the social optimum generally requires a system of transfers that redistributes income among generations (Gerlagh and Keyzer, 2001; 2003).

The idea that sustainable development is a matter of intergenerational equity, rather than of technological feasibility, is the main conceptual difference between the two strands of literature described above. The distinction is further emphasized at the formal level: most contributions studying endogenous growth models do not consider explicit demographic structures, while overlapping generations models generally neglect endogenous growth mechanisms. However, merging the two frameworks is desirable from the perspective of both positive and normative analysis, since assuming infinitely-lived agents prevents any systematic study of the links between the source of endogenous growth and the intergenerational distribution of resources. Building on this general idea, this paper tackles the specific issues of (i) the interactions between equilibrium rates of resource use and human capital accumulation in both laissez-faire and optimized economies, and (ii) the way in which these interactions affect the intergenerational distribution of benefits.

From a theoretical perspective, the reason for addressing these issues is twofold. A first point regards the role of human capital formation in relieving the constraints imposed by resource scarcity. Differently from resource-augmenting technical progress - i.e. innovations that are expressly designed to raise the productivity of natural resources (Amigues et al. 2004; Di Maria and Valente, 2006) - increasing the rate of human capital accumulation may have non-trivial effects, since higher study time tends to crowd-out individual private wealth. The net effect of increased knowledge formation on the share of natural resources that is being given to subsequent generations is not clear a priori, as it depends on the nature of intertemporal trade relations. In this regard, we will assume a world of selfish agents, where resources are sold to successors only to the extent that preservation is profitable to those currently alive.

[3] The Brundtland Energy Report (WCED, 1987) defined sustainable development as development that meets the needs of the present, without compromising the ability of future generations to meet their own needs. In formal economic models, this definition has been translated in terms of conditions requiring that (i) the utility level achieved by each generation not exceed the maximum level of utility that can be sustained forever by the economy, or (ii) the level of utility of each generation be at least equal to that enjoyed by the previous generation (see Pezzey, 1992).

A second question regards the role of present-value optimality and social discounting in centrally-planned allocations. Models with infinitely-lived agents tend to support the view that discounting harms prospects for sustainability, since a high rate of time preference may yield negative growth rates in the long run. The reasoning is quite different in an overlapping-generations setting where bequests are not operative. Imposing intergenerational discounting in these models introduces a minimal concern for fairness in the criterion of social optimality: the resulting allocations are still biased in favor of early-in-time consumption, but late-in-time generations receive benefits with respect to selfish laissez-faire. The literature on this issue emphasized this point in the general context of complete markets - an early reference is Howarth and Norgaard (1993) - but little attention has been given to situations in which the problem of allocating scarce resources among selfish agents is combined with intergenerational externalities induced by human capital. This point is relevant, however, since the inclusion of dynamic spillovers reshapes optimal allocations, modifies the design of intergenerational transfers, and obviously affects the intergenerational distribution of welfare gains from optimal policies. The coexistence of intergenerational externalities and exhaustible resources is the central feature of the present analysis: when human capital accumulation is sustained by knowledge spillovers, redistribution becomes desirable even from a purely utilitarian point of view. In general, this implies that redistributing toward future generations is optimal, but, as we show, does not necessarily mean that resource depletion rates will be lower than under laissez-faire. Moreover, since redistribution also implies 'level effects' on output, another relevant issue regards the welfare consequences of the interaction between human and natural capital for the different generations involved.

Beyond the theoretical issues, studying these interactions is also relevant from an empirical perspective. Applied studies by Gylfason (2001), Bravo-Ortega and De Gregorio (2005), and Stijns (2006), suggest that human capital formation has been a key determinant of the economic performance of many resource-dependent countries. Great abundance of non-renewable natural inputs, such as oil, is associated with stagnation in countries where human capital is relatively low, whereas sustained growth is observed in economies where workers are well-endowed with education and skills. In particular, Bravo-Ortega and De Gregorio (2005) study the relative performance of Scandinavian and Latin American economies, finding a significant 'interaction term' between human capital and resource exploitation.

In secion 2 we study a simple endogenous growth model where individual knowledge is positively affected by the average human capital of previous generations, and can be raised by means of education. The natural stock represents aggregate private wealth, and can be either sold to successors or employed in

production. It is shown that, in the laissez-faire economy, the higher is study time, the higher is the share of resources that adult agents are willing to sell to future generations - and, symmetrically, the lower is the share of natural capital sold to firms for production purposes. However, selfish behavior may prevent sustained growth under laissez-faire. In the command optimum, the speed at which natural capital declines over time is negatively correlated with the rate of human capital accumulation, through the social discount rate. This implies that human capital accumulation and resource preservation are always complementary targets in optimal policies: although knowledge spillovers are the only externality, resource entitlements must also be reallocated across generations in order to implement the social optimum. Depending on the level of the discount rate, optimal allocations exhibit different characteristics: with heavy discounting, they are knowledge-improving but imply faster depletion rates relative to the laissez-faire equilibrium; when the social discount rate falls below a critical threshold, instead, the optimal allocation displays higher study time and reduced rates of resource use. As shown in section 3, both strategies are generally growth-enhancing, and bring the economy toward optimal and sustainable paths, but welfare implications differ: when optimal are resource-saving, growth effects are stronger and contrast negative level effects induced by redistribution. This 'welfare-compensation mechanism', not observable in models with infinitely-lived agents, implies that early-in-time generations enjoy positive welfare gains from optimal allocations especially when the associated policy is resource-preserving - i.e. characterized by low discount rates. Conversely, the achievement of positive net benefits may be delayed substantially by high discount rates: the reason for this counter-intuitive result is that heavy social discounting implies resource-depleting optimal policies. Section 4 summarizes the conclusions, and suggests two possible extensions of the present analysis.

2 The model

We assume that positive production requires natural capital, in addition to human capital. Differently from the 'sustained growth literature', which postulates that the engine of growth is technological progress driven by R&D activity, economic development is here induced by intergenerational spillovers that sustain human capital accumulation (Uzawa, 1965; Lucas, 1988). The model can thus be considered an extension of the Uzawa-Lucas framework (e.g. Azariadis and Drazen, 1990; Docquier and Michel, 1999) to include exhaustible resources; or, symmetrically, an extension of the labor-resource model with overlapping generations (Mourmouras, 1993; Krautkraemer and Batina, 1999; Valente, 2007) to

include human capital formation.[4]

For simplicity, we assume zero net fertility rates: in each period t, the economy is populated by n young and n adult individuals. Lifetime utility of an agent born at the beginning of period t depends on individual consumption when young, c_t, and when adult, e_{t+1}, with preferences

$$V_t = \log c_t + \beta \log e_{t+1}, \tag{1}$$

where $\beta \in (0,1)$ is the private discount factor. In line with recent literature, a sustainable path is defined as path along which lifetime utility is non-declining over time - that is, $V_{t+1}(c_{t+1}, e_{t+2}) \geq V_t(c_t, e_{t+1})$. In period t, there are n young and n adult individuals, and each young agents inherits own knowledge from the current state of the economy. Knowledge is represented by $\bar{h}$, measured in terms of labor-efficiency units. Individuals are endowed with one unit of time: in the first period of life, a fraction $(1-\ell_t)$ is devoted to study, and $\ell_t \bar{h}_t$ are supplied for production. In the second period, individuals only work, and consume all their income. The level of labor efficiency achieved at the beginning of the second period of life depends on study time, according to the learning technology

$$\bar{h}_{t+1} = \varphi_t \bar{h}_t, \qquad \varphi_t = \psi (1-\ell_t)^{\varepsilon}, \tag{2}$$

where φ exhibits decreasing returns, $0 < \varepsilon < 1$, and $\psi > 0$ is a proportionality factor. Aggregate human capital, H, is the amount of labor supplied by the two generations alive in period t. Denoting by $h_t = n\bar{h}_t$ the amount of knowledge in each cohort, aggregate human capital at time t equals $H_t = (1+\ell_t) h_t$. Since agents are assumed to be homogeneous, total labor supply evolves according to

$$H_{t+1} = H_t \varphi_t \left(\frac{1+\ell_{t+1}}{1+\ell_t} \right). \tag{3}$$

The economy is also endowed at time zero with a stock of natural resources, $R_0 > 0$. Natural resources are essential for production and are privately owned by agents. In this regard, we assume a grandfathering process *à la* Krautkraemer and Batina (1999): at the beginning of period t, the whole stock of resources

[4] Mourmouras (1993) uses the overlapping-generations setup to demonstrate that competition may lead to over-exploitation of privately-owned renewable resources, and describes a set of conservationist policies that implement the *Rawlsian path* - *i.e.* policies that keep private welfare constant, at the highest feasible level, across generations. In the same setting, Krautkraemer and Batina (1999) analyze intergenerational transfers assuming that resource regeneration rates are stock-dependent, whereas Valente (2007) studies the conditions under which newborn generations strictly prefer resource-saving policies to laissez-faire conditions.

R_t is held by adults. Part of R_t is used as natural capital in production, X, while the remaining stock constitutes resource assets, A. Since the resource is non-renewable, the resource stock equals $R_t = A_t + X_t$ in each period, and evolves over time according to

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

Adults sell resource assets A at unit price q, and receive a gross marginal rent p for each unit of natural capital X supplied to firms. Aggregate output, Y, is produced by means of human and natural capital according to the production function $Y_t = X_t^{\alpha} H_t^{1-\alpha}$, with $0 < \alpha < 1$. Defining $k \equiv H/X$, the output-natural capital ratio $y_t \equiv Y_t/X_t$ equals

$$y_t = k_t^{1-\alpha}. \tag{5}$$

It follows from the above assumptions that prospects for sustainability depend not only on human capital formation, but also 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.

2.1 Laissez-faire competitive equilibrium

In view of constant returns to scale, the production sector can be represented as a single competitive firm: denoting by w the wage rate, profit maximization implies

$$w_t = (1-\alpha)\, k_t^{-\alpha} \text{ and } p_t = \alpha k_t^{1-\alpha} = \alpha y_t. \tag{6}$$

As regards consumers, individual budget constraints read

$$c_t = w_t \ell_t \bar{h}_t - q_t a_t, \tag{7}$$

$$e_{t+1} = p_{t+1} x_{t+1} + q_{t+1} a_{t+1} + w_{t+1} \bar{h}_{t+1}, \tag{8}$$

where $a \equiv A/n$ and $x \equiv X/n$ are individual amounts of resource assets and natural capital, respectively. Individual constraints (7)-(8) conveniently summarize the trade-off between studying and working faced by young agents: higher study time yields higher returns from labor in the second period, but lower work time when young reduces possibilities for first-period consumption and accumulation of resource assets. Since the resource market is fully competitive, equilibrium requires $p_t = q_t$ at each point in time: using (4), constraint (8) can be written as

$$e_{t+1} = p_{t+1} r_{t+1} + w_{t+1} \bar{h}_{t+1} = i_{t+1} q_t a_t + w_{t+1} \bar{h}_{t+1}, \tag{9}$$

where we have defined i_{t+1} as the implicit interest factor on resource assets.

The consumer problem is solved in two steps. First, agents choose the amount of work time that maximizes the present value of lifetime income, $w_t \ell_t \bar{h}_t + w_{t+1} \bar{h}_{t+1} i_{t+1}^{-1}$, subject to the learning technology (2). In the second step, consumers maximize lifetime utility (1) subject to the budget constraints (7)-(9). The resulting first-order conditions imply

$$\begin{aligned} w_{t+1} \varepsilon \varphi_t &= w_t (1 - \ell_t) i_{t+1}, & (10) \\ p_{t+1}/p_t &= q_{t+1}/q_t = i_{t+1}, & (11) \\ e_{t+1} &= \beta c_t i_{t+1}. & (12) \end{aligned}$$

Equation (10) characterizes the optimal allocation of time between studying and working, and simply asserts that the marginal cost of raising private knowledge (in terms of labor income that is forgone due to studying) must match its marginal benefit (higher future labor income in present-value terms). Expression (11) is the Hotelling rule, which asserts that resource assets are efficiently managed over time if the growth rate of the marginal reward to natural capital equals the rate of return to private wealth. Equation (12) is the standard Euler condition for consumption allocation over the life-cycle. Substituting equilibrium prices (6) in the budget constraints (7)-(9) we obtain the aggregate constraint of the economy,

$$Y_t = C_t + E_t, \tag{13}$$

where $C_t = nc_t$ and $E_t = ne_t$.

The decentralized equilibrium can be characterized as follows. Define the natural capital-resource asset ratio as $z_t \equiv X_t / A_t$. This index is inversely related to the degree of resource preservation, since the higher is z the lower is the share of resources that is saved in the form of private assets. By this definition, we can write

$$\frac{X_{t+1}}{X_t} = \frac{z_{t+1}}{z_t (1 + z_{t+1})} \text{ and } \frac{X_{t+1}}{X_t} = \frac{(1 - \ell_t)(1 + \ell_{t+1})}{\varepsilon (1 + \ell_t)}, \tag{14}$$

where the first expression derives from (4), and the second expression is the equilibrium growth rate of natural capital implied by (10) and (11). From (14), the transition law for z reads

$$\frac{z_{t+1}}{1 + z_{t+1}} = z_t \frac{(1 - \ell_t)(1 + \ell_{t+1})}{\varepsilon (1 + \ell_t)}. \tag{15}$$

Next, substitute conditions (10)-(11)-(12) in the budget constraints (7)-(9) to obtain

$$z_t = \frac{1 + \beta}{1 - \alpha} \left[\frac{\alpha \varepsilon (1 + \ell_t)}{\beta \varepsilon \ell_t - (1 - \ell_t)} \right]. \tag{16}$$

From (15) and (16), there exists a forward-looking condition determining the equilibrium value of work time of young agents of the type $\ell_{t+1} = \chi(\ell_t)$. Plugging (16) in (15) to substitute z_t and z_{t+1}, and defining parameters

$$b_0 \equiv \frac{\beta\varepsilon^2(1-\alpha)}{1-\alpha+\varepsilon(\alpha+\beta)} > 0 \text{ and } b_1 \equiv \frac{(1-\varepsilon)(1-\alpha)-\alpha\varepsilon(1+\beta)}{1-\alpha+\varepsilon(\alpha+\beta)}, \tag{17}$$

the relation $\ell_{t+1} = \chi(\ell_t)$ takes the hyperbolic form

$$\ell_{t+1} = \chi(\ell_t) = b_0\left(\frac{\ell_t}{1-\ell_t}\right) + b_1. \tag{18}$$

The optimal amount of work time supplied by young generations determines, together with (3) and (14), the temporary equilibrium of the economy, which is defined at given expectations over the future interest factor and the future employment level. Similar models are characterized by stationary solutions, where work time jumps at the equilibrium level at time zero and is constant thereafter (see de la Croix and Michel, 2002: Chap.5). Also in the present context, work time exhibits a stationary solution which is described in the following

Lemma 1 *In the decentralized competitive equilibrium, there exists a unique stationary solution $\ell^\star = \chi(\ell^\star)$ that satisfies optimality conditions with positive production. In equilibrium, work time supplied by young agents is equal to $\ell^\star$ in each period, with*

$$\ell^\star = (1/2)\left[1-b_0+b_1+\sqrt{(1-b_0+b_1)^2-4b_1}\right], \tag{19}$$

$$\ell^\star > \frac{1}{1+\beta\varepsilon}. \tag{20}$$

Proof. First notice that $\chi(.)$ is increasing and convex,

$$\frac{\partial\chi(\ell_t)}{\partial\ell_t} = b_0\frac{(2-\ell_t)}{(1-\ell_t)^2} > 0, \qquad \frac{\partial^2\chi(\ell_t)}{\partial\ell_t^2} = b_0\frac{(3-\ell_t)}{(1-\ell_t)^3} > 0, \tag{21}$$

and that

$$\lim_{\ell_t\to 1}\chi(\ell_t) = +\infty \text{ and } \lim_{\ell_t\to 0}\chi(\ell_t) = b_1. \tag{22}$$

Depending on the constellation of parameters, we may have two cases, $b_1 < 0$ or $b_1 > 0$. In the first case, $b_1 < 0$, the second limit in (22) implies that there exists

a unique stationary equilibrium ℓ^{ss} such that $\ell^{ss} = \chi(\ell^{ss}) > 0$. Moreover, the condition $\ell^{ss} = \chi(\ell^{ss})$ implies

$$\frac{b_0}{1-\ell^{ss}} = \frac{\ell^{ss} - b_1}{\ell^{ss}} > 1. \tag{23}$$

From (21) and (23) it follows that

$$\left.\frac{\partial \chi(\ell_t)}{\partial \ell_t}\right|_{\ell_t=\ell^{ss}} = \frac{b_0}{1-\ell^{ss}}\left(\frac{2-\ell^{ss}}{1-\ell^{ss}}\right) > 1,$$

which proves that ℓ^{ss} is unstable. As a consequence, $\ell^{ss} = \ell^{\star}$ as defined in (19): work time of young agents jumps at $\ell^{\star}$ at time zero and remains constant thereafter (see Figure 1.a). In the second case, $b_1 > 0$, there are two stationary solutions with positive work time: setting $\ell_{t+1} = \ell_t$ in (18) yields two roots, ℓ_1^{ss} and ℓ_2^{ss} (see Figure 1.b). The first is given by the right hand side of (19), and satisfies $\ell_1^{ss} > \ell_2^{ss}$ due to the positive sign in front of the square root. As before, ℓ_1^{ss} is compatible with optimality conditions and positive production. Root ℓ_2^{ss} appears incompatible with positive production instead: since resources are essential, $z_t > 0$ is strictly required, which implies, from the denominator in (16), that equilibrium work time must exceed the lower bound $(1+\beta\varepsilon)^{-1}$. All numerical substitutions performed, including the set of parameters used in the various simulations presented, show that this constraint is violated by the second root, so that $\ell_2^{ss} = \ell^{\star}$ can be safely rejected on the grounds that

$$\ell_2^{ss} = (1/2)\left[1 - b_0 + b_1 - \sqrt{(1-b_0+b_1)^2 - 4b_1}\right] < (1+\beta\varepsilon)^{-1}.$$

An example is reported in Figure 1.b: even when $b_1 > 0$, the only solution satisfying optimality conditions is $\ell_1^{ss} = \ell^{\star}$. ■

Given that work time equals $\ell^{\star}$ in each period, the decentralized economy follows a balanced growth path from time zero onward. Setting $\ell_t = \ell^{\star}$ in (16), the natural capital-resource asset ratio is constant: from (14), the resource stock is depleted at a constant rate, and the same rate of variation applies to natural capital and resource assets. Constant work time implies a constant rate of human capital accumulation in (3), and therefore a constant growth rate of aggregate output. Denoting by superscript '$\star$' the equilibrium values in the competitive equilibrium, the following proposition holds.

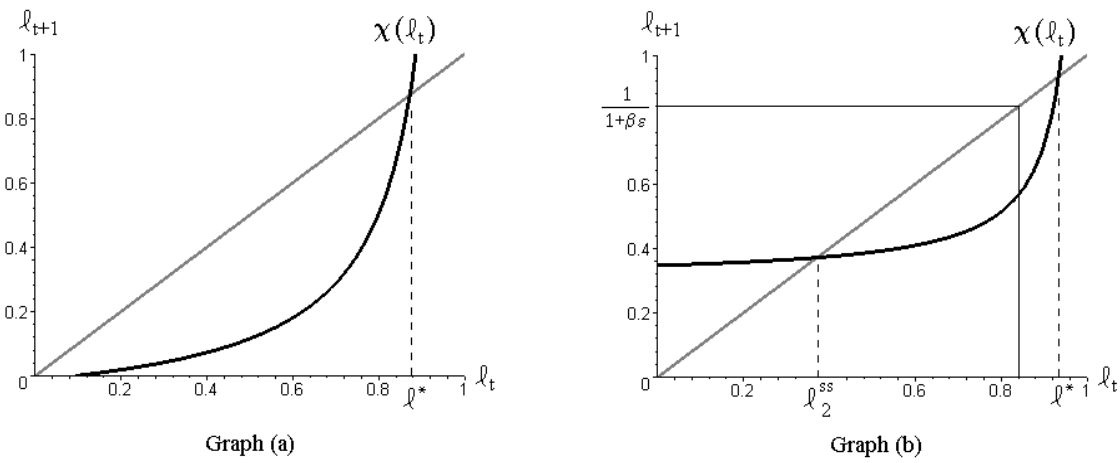

Figure 1: Examples of stationary solutions for work time in the decentralized equilibrium. Graph (a): when $b_1 < 0$ there exists a unique equilibrium ($\alpha = 0.3$, $\beta = 0.65$, $\varepsilon = 0.6$). Graph (b): when $b_1 > 0$ there exists a second solution $\ell_2^{ss} < \ell_1^{ss}$ but it violates optimality conditions ($\alpha = 0.3$, $\beta = 0.65$, $\varepsilon = 0.3$). The other solution thus represents the equilibrium.

Proposition 2 *The decentralized competitive equilibrium exhibits balanced growth from time zero onwards, with*

$$H_{t+1}^\star / H_t^\star = \varphi^\star = \psi \left(1 - \ell^\star\right)^\varepsilon, \tag{24}$$

$$X_{t+1}^\star / X_t^\star = R_{t+1}^\star / R_t^\star = \left(1 + z^\star\right)^{-1}, \tag{25}$$

$$Y_{t+1}^\star / Y_t^\star = C_{t+1}^\star / C_t^\star = E_{t+1}^\star / E_t^\star = \left(1 + z^\star\right)^{-\alpha} \left(\varphi^\star\right)^{1-\alpha}, \tag{26}$$

where the rate of resource use is linked to study time by

$$\frac{1}{1 + z^\star} = \frac{1 - \ell^\star}{\varepsilon}. \tag{27}$$

Recalling that $z^\star$ represents the net rate of decline in $X_t^\star$, the equilibrium relation (27) implies that study time is positively correlated with both knowledge accumulation and the speed at which natural capital is being exploited. Substituting (27) in (26) we have

$$Y_{t+1}^\star / Y_t^\star = \underbrace{\left[\varepsilon^{-1}\left(1 - \ell^\star\right)\right]}_{\text{Indirect effect}}^{\alpha} \underbrace{\left[\psi\left(1 - \ell^\star\right)^\varepsilon\right]}_{\text{Direct effect}}^{1-\alpha}. \tag{28}$$

Expression (28) clarifies that a ceteris paribus increase in $\ell^\star$ - e.g. induced by variations in the time-preference rate β - raises the economy's growth rate not

only by stimulating human capital accumulation (direct effect), but also limiting the rate of depletion of natural capital (indirect effect). Indeed, the higher is study time, the more natural resources are substituted in production by human capital; consequently, adult agents sell a higher share of the current stock to future generations in the form of resource assets - and, symmetrically, a lower share to firms for production purposes.[5] The underlying mechanism may thus be labelled as crowding-out, although it is a type of crowding-out that is beneficial to growth: human capital complements resource preservation, and both help sustaining economic growth.

Expression (26) implies that the propensities to consume remain constant over time: plugging this result in preferences (1), it derives that lifetime-utility levels $V_t^\star$ are linear in the logarithm of output at time t - see (53) below. As a consequence, a necessary and sufficient condition for sustainability in the decentralized equilibrium is that $Y_{t+1}^\star / Y_t^\star \geq 1$. Notice that, under laissez-faire, negative growth rates are not a remote possibility, since selfish behavior harms prospects for sustainability to a great extent. In section 3, we will analyze the situations in which the laissez-faire economy displays unsustainability, characterizing the set of policies that implement optimal and sustainable paths.

2.2 Utilitarian Command Optimum

The distinctive feature of the Lucas-Uzawa framework is that endogenous growth is driven by an intergenerational externality. Dynamic knowledge spillovers make the laissez-faire path sub-optimal from the point of view of discounted utilitarianism, and thus provide a rationale for policies that modify the rate of human capital accumulation (Azariadis and Drazen, 1990; Docquier and Michel, 1999). In the presence of natural resources, however, implementing the utilitarian solution likely bears side-effects on the rate of resource extraction, since we may expect an interaction between human and natural inputs similar to that arising in the laissez-faire economy. Assume that a benevolent social planner is able to choose the sequence of consumption levels, work time and resource extraction.

[5] This result follows from the fact that agents simultaneously satisfy two conditions that prevent intertemporal arbitrage (over natural and human capital, respectively). To see this formally, impose interest-rate equalization in (10) and (11) to get

$$i_{t+1}^\star = \left(\frac{k_{t+1}^\star}{k_t^\star}\right)^{1-\alpha} = \frac{\varepsilon\varphi^\star}{(1-\ell^\star)}\left(\frac{k_{t+1}^\star}{k_t^\star}\right)^{-\alpha},$$

from which the growth rate of $k_t^\star$ can be written ratio in terms of parameters and equilibrium study-time. Subsituting (24) and (25) yields (26).

The social problem consists of maximizing the discounted sum of lifetime utilities

$$\sum_{t=0}^{\infty} \left[\log\left(C_t\right) + \beta \log\left(E_{t+1}\right)\right] \Phi^t, \tag{29}$$

where $\Phi \in (0,1)$ is the social discount factor. The objective function (29) is utilitarian in spirit, and is deliberately chosen in order to strengthen the idea that sustainable paths can be a by-product of optimal policies even though the social goal does not incorporate specific concerns. The utilitarian optimum is defined as a path $\{C_t^u, E_t^u, \ell_t^u, X_t^u\}_{t=0}^{\infty}$ that maximizes (29) subject to the learning technology (3), the natural resource constraint (4), and the aggregate constraint of the economy (13). The associated Lagrangean is

$$\begin{aligned}\mathcal{L} \;=\; & \sum_{t=0}^{\infty} \left\{\left[u\left(C_t\right) + \beta u\left(E_{t+1}\right)\right] \Phi^t + \lambda_t^y \left[X_t^{\alpha} h_t^{1-\alpha} \left(1+\ell_t\right)^{1-\alpha} - C_t - E_t\right] + \right. \\ & \left. + \lambda_t^h \left(\varphi_t h_t - h_{t+1}\right) + \lambda_t^r \left(R_t - X_t - R_{t+1}\right)\right\},\end{aligned}$$

where λ_t^y, λ_t^h, and λ_t^r, are dynamic multipliers representing the social marginal shadow values of income, knowledge formation and resource depletion, respectively. The necessary conditions for optimality are

$$\begin{aligned}
\mathcal{L}_{c_t} &= 0 \qquad \Phi^t / C_t = \lambda_t^y, && (30)\\
\mathcal{L}_{e_{t+1}} &= 0 \qquad \Phi^t \beta / E_{t+1} = \lambda_{t+1}^y, && (31)\\
\mathcal{L}_{x_t} &= 0 \qquad \lambda_t^y \alpha X_t^{\alpha-1} H_t^{1-\alpha} = \lambda_t^r, && (32)\\
\mathcal{L}_{\ell_t} &= 0 \qquad \lambda_t^y \left(1-\alpha\right) X_t^{\alpha} h_t^{1-\alpha} \left(1+\ell_t\right)^{-\alpha} = -\lambda_t^h \varphi_{\ell_t} h_t, && (33)\\
\mathcal{L}_{h_t} &= 0 \qquad \lambda_t^y \left(1-\alpha\right) X_t^{\alpha} h_t^{-\alpha} \left(1+\ell_t\right)^{1-\alpha} + \lambda_t^h \varphi_t = \lambda_{t-1}^h, && (34)\\
\mathcal{L}_{r_t} &= 0 \qquad \lambda_t^r = \lambda_{t-1}^r, && (35)
\end{aligned}$$

together with the usual transversality conditions for the co-state variables, h_t and R_t. On the basis of these conditions, denoting by superscript 'u' the optimal values in the utilitarian solution, we have

$$\begin{aligned}
E_{t+1}^u &= \beta C_t^u \left(k_{t+1}^u / k_t^u\right)^{1-\alpha}, && (36)\\
k_{t+1}^u / k_t^u &= -\varphi_{\ell}^u + \varphi^u \left[1 + \varepsilon \ell^u \left(1-\ell^u\right)^{-1}\right], && (37)\\
X_{t+1}/X_t &= \left(1+z^u\right)^{-1}, && (38)\\
z^u &= \varepsilon \left(1+\ell^u\right)\left(1-\ell^u\right)^{-1}. && (39)
\end{aligned}$$

The amount of work time ℓ^u can be derived as follows. First, note that (30) and (31) imply constant propensities to consume, $C_t/Y_t = \Phi\left(\beta+\Phi\right)^{-1}$ and $E_t/Y_t =$

$\beta(\beta+\Phi)^{-1}$. Substituting these expressions in (36) gives $X_{t+1}/X_t = \Phi$. By definiton, the social discount rate is $\rho \equiv \Phi^{-1} - 1$, so that $z^u = \rho$. Condition (39) then implies

$$\ell^u = \frac{\rho - \varepsilon}{\rho + \varepsilon} < 1. \tag{40}$$

Hence, the lower is the social discount rate, the higher is study time, $1 - \ell^u$, and the lower is the rate of resource depletion. Substituting (40) in conditions (36)-(39) we obtain the following

Proposition 3 *The utilitarian solution exhibits balanced growth equilibrium from time zero onward, with*

$$\begin{aligned} H^u_{t+1}/H^u_t &= \varphi^u = \psi\left(1-\ell^u\right)^{\varepsilon}, && (41)\\ X^u_{t+1}/X^u_t &= R^u_{t+1}/R^u_t = \left(1+z^u\right)^{-1}, && (42)\\ Y^u_{t+1}/Y^u_t &= C^u_{t+1}/C^u_t = E^u_{t+1}/E^u_t = \left(1+z^u\right)^{-\alpha}\left(\varphi^u\right)^{1-\alpha}, && (43) \end{aligned}$$

where the rate of resource use is linked to study time by

$$z^u = \rho = \varepsilon\left(\frac{1+\ell^u}{1-\ell^u}\right). \tag{44}$$

Expression (44) shows that, similarly to the laissez-faire case, the rate of resource use is negatively correlated with study time. However, the nature and consequences of this interaction are quite different. From (40) and (43), output growth can be expressed as

$$\frac{Y^u_{t+1}}{Y^u_t} = \underbrace{\left(\frac{1}{1+\rho}\right)^{\alpha}}_{\text{Resource-use effect}} \underbrace{\left[\psi\left(\frac{2\varepsilon}{\rho+\varepsilon}\right)^{\varepsilon}\right]^{1-\alpha}}_{\text{Study-time effect}}. \tag{45}$$

From (45), a reduction in ρ increases the optimal growth rate through two channels: lower discount rates increase optimal study time - which stimulates human capital accumulation - but also imply slower rates of optimal depletion, because the weight that is put on the utility of late-in-time generations is higher. This interaction between human and natural capital can be interpreted in terms of policy objectives. If public authorities want to implement the utilitarian allocation in a decentralized competitive economy, the task of economic policy is twofold: first, it is necessary to support an optimal level of study time,$1 - \ell^u$, in order to internalize knowledge spillovers; second, parallel actions must be taken to redistribute resource entitlements across generations, in order to implement

the optimal rate of resource depletion. Knowledge formation and resource preservation are thus complementary targets. In the next section we exploit (45) to characterize utilitarian solutions - and, by extension, optimal policies - in both regards.

3 Growth, Fairness and Social Discounting

The analysis of section 2.2 suggests that optimal policies - i.e. public actions aimed at implementing the command-optimum allocation in a decentralized economy - exhibit different properties depending on the assumed social discount rate. This allows us to characterize optimal policies in a consequentialist way, i.e. not in terms of specific fiscal instruments, but rather in terms of the consequences for equilibrium study time and the speed of depletion of natural capital.

3.1 Characterization of optimal policies

For expositional clarity, we will exploit the following definitions. First, if utilitarian solutions exhibit slower resource depletion than laissez-faire, implementing the social optimum requires an intertemporal redistribution of entitlements that is labelled *R-preserving policy*. Second, if they exhibit higher study time, the optimal allocation is associated with *H-enhancing policies*. Third, if the utilitarian solution features a positive net growth rate of output, the optimal allocation is characterized by *sustainability*. These situations can be represented in terms of different values of the social discount rate. By definition, R-preserving policies arise when $z^u < z^\star$, which, from (44) is equivalent to the condition

$$\rho < z^\star = \frac{\varepsilon}{1-\ell^\star} - 1. \tag{46}$$

When (46) does not hold because $\rho > z^\star$, optimal policies are *R-depleting*. In the special case $\rho = z^\star$, policies are *R-neutral*.

As regards H-enhancing policies, it derives from (40) that optimal study time is higher than laissez-faire study time if

$$\rho < \hat{\rho} \equiv \frac{\varepsilon}{1-\ell^\star}\left(1+\ell^\star\right), \tag{47}$$

where we have defined the upper-bound for H-enhancing policies as $\hat{\rho}$. It derives from (46) and (47) that $z^\star < \hat{\rho}$. This means that R-preserving optimal policies are necessarily H-enhancing, but the converse is not true. That is, optimal policies generally raise study time with respect to laissez-faire - in line with the established

result that improving knowledge formation is desirable - but may not reduce the rate of resource depletion: when $z^\star < \rho < \hat{\rho}$, both study time and depletion rates will exceed the respective laissez-faire values.

In order to assess the consequences of R-preserving and R-depleting policies for growth and intergenerational fairness, we also characterize sustainability outcomes. In the utilitarian solution, sustainability requires $Y_{t+1}^u / Y_t^u \geq 1$.[6] Defining the functions

$$g^A(\rho) = \left[\psi \left(\frac{2\varepsilon}{\rho + \varepsilon}\right)^{\varepsilon}\right]^{\frac{1-\alpha}{\alpha}} \text{ and } g^B(\rho) = 1 + \rho, \tag{48}$$

it derives from (45) that $Y_{t+1}^u / Y_t^u \geq 1$ is satisfied if and only if $g^A(\rho) \geq g^B(\rho)$. Since $g^A(.)$ is monotonically decreasing and $g^B(.)$ is monotonically increasing, if $g^A(0) > g^B(0) = 1$ the 'sustainability set' is non-empty, and there is a unique $\bar{\rho}$ satisfying $g^A(\bar{\rho}) = g^B(\bar{\rho})$. This threshold level represents the critical upper-bound for the social discount rate to allow for sustained output and welfare in the social optimum. As a consequence, the utilitarian solution implies an *optimal and sustainable path* if

$$\rho \leq \bar{\rho}. \tag{49}$$

Since condition (49) imposes another upper-bound on the social discount rate, sustainability is more likely to arise when ρ is relatively low - in particular, when optimal policies are R-preserving. However, since the threshold level $\bar{\rho}$ may be greater or less than $z^\star$, there generally exists the possibility that also R-preserving optimal policies guarantee sustainable and optimal paths. In the next section, we describe the implications of R-preserving versus R-depleting policies for growth rates, output levels, and intergenerational fairness.

3.2 The welfare-compensation mechanism

As noted in section 2.1, negative growth is not a remote possibility under laissez-faire, since selfish behavior crucially harms prospects for sustainability. Having characterized utilitarian allocations, of particular interest is the situation in which parameters imply the laissez-faire economy be unsustainable. Figure 2 reports two cases in which the laissez-faire equilibrium implies declining output and welfare over time. As expected, sustainable and optimal paths require H-enhancing optimal policies in both cases ($\bar{\rho} < \hat{\rho}$). Moreover, in graph (a), sustainability

[6] As in the laissez-faire case, balanced growth in the social optimum implies lifetime utility V_t^u be linear in the logarithm of output levels at time t - see expression (54) - so that a necessary and sufficient condition for sustainability in the social optimum is $Y_{t+1}^u / Y_t^u \geq 1$.

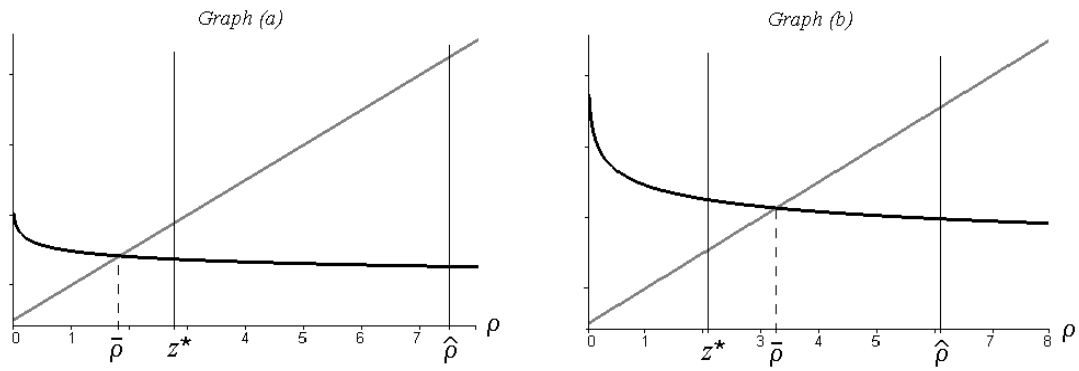

Figure 2: Characterization of optimal policies. The sustainability threshold $\bar{\rho}$ is obtained using the condition $g^A = g^B$, as explained in (48). Graph (a): parameters are $\alpha = 0.2$, $\varepsilon = 0.02$, $\beta = 0.55$, $\psi = 1.4$. Sustainable optimal paths requires H-ehnancing and R-preserving policies. Graph (b) parameters are $\alpha = 0.2$, $\varepsilon = 0.03$, $\beta = 0.75$, $\psi = 1.62$. Sustainability requires H-ehnancing policies, but not necessarily R-preserving policies.

requires the optimal policy be both H-enhancing and R-preserving: since $\bar{\rho} < z^\star$, sustainable and optimal paths arise only if study time is increased and depletion rates are reduced. In graph (b), instead, sustainable policies may also be R-depleting: if the social discount rate falls within the critical range, $z^\star < \rho < \bar{\rho}$, optimal policies raise study time as well as resource use with respect to laissez-faire.

The consequences of R-depleting and R-preserving policies clearly differ in terms of growth effects, level effects, and intergenerational welfare. Recalling (45), low discount rates guarantee stronger growth effects. Level effects go in the opposite direction: iterating (24) and (25) with constant ℓ and z yields

$$H_t = h_0 (1+\ell) \left[\psi (1-\ell)^{\varepsilon}\right]^t, \tag{50}$$

$$X_t = \left(\frac{1}{1+z}\right)^t X_0 = \frac{z}{1+z}\left(\frac{1}{1+z}\right)^t R_0, \tag{51}$$

and, substituting these results in the aggregate technology, we obtain the time path of output:

$$Y_t = \left(\frac{z}{1+z}\right)^{\alpha} R_0^{\alpha} h_0^{1-\alpha} (1+\ell)^{1-\alpha} \left[\left(\frac{1}{1+z}\right)^{\alpha} \psi^{1-\alpha} (1-\ell)^{\varepsilon(1-\alpha)}\right]^t. \tag{52}$$

Setting $t = 0$ we obtain $\partial Y_0/\partial \ell > 0$ and $\partial Y_0/\partial z > 0$, which implies unambigu-

ously negative level effects of reduced discount rates.[7]

The above reasoning suggests that low discount rates - i.e. more intense R-preserving optimal policies - generate level effects that tend to reduce benefits for early-in-time generations. Expression (52) shows that this is obviously true in terms of output, and one would expect that the same process affects welfare levels. In the latter regard, however, results are not so intuitive, and this is a peculiar consequence of assuming overlapping generations. As shown below, R-depleting optimal policies may delay the achievement of welfare gains substantially, whereas R-preserving optimal policies yield positive net benefits for early-in-time generations.

Since agents consume output in different periods, level-effects on Y are quite different from level-effects on lifetime utility, V: from the optimality conditions in both laissez-faire and utilitarian regimes, we obtain (see Appendix)

$$V_t^\star = F'(\ell^\star, z^\star) + (1+\beta)\log Y_t^\star, \tag{53}$$

$$V_t^u = F''(\ell^u, z^u) + (1+\beta)\log Y_t^u. \tag{54}$$

The presence of both ℓ and z in intercept-terms, F' and F'', elucidates the fact that positive *growth* effects on *output* yield further *level* effects on *welfare*. For example, if we implement growth-enhancing policies, reduced first-period consumption tends to be compensated, at least in part, by increased second-period consumption. This 'welfare-compensation mechanism' is generally not observable in standard models with infinitely-lived consumers. The general implication is that policies that induce strong growth effects contrast the negative level effects generated by redistribution in the long run. This may imply positive welfare gains already for the first newborn generation: when optimal output is initially below the laissez-faire level, $Y_0^u < Y_0^\star$, but growth effects imply $Y_1^u > Y_1^\star$, we can obtain a strictly positive net effect on welfare, $V_0^u > V_0^\star$. This mechanism also generates an apparently counter-intuitive result: since the intensity of growth effects is inversely related with social discount rates, heavy social discounting delays the achievement of (lifetime) utility gains, whereas moderate discount rates anticipate the achievement of welfare improvements. In particular, more intense R-preserving policies are more likely to make early-in-time generations better off with respect to laissez-faire conditions.

Figure 3 and Table 1 illustrate this result in graphical and numerical terms. In Cases I and II, utilitarian allocations imply lower output levels (relative to laissez-faire) in the very short run, but the net effect on lifetime welfare of the first

[7] Notice that expression (52) is also valid under laissez-faire: output levels associated with higher equilibrium study time tend to be lower in the short run.

newborn generation is strictly positive, even for very high rates of social discount. The fact that cohorts born at $t = 0$ represent the 'first happy generation' may seem striking but is not bizarre: as Gale (1973) first pointed out, intergenerational redistribution can make all agents born at $t \geq 0$ better off, provided that those who are adult at $t = 0$ renounce part of their entitlements over existing resources to the benefit of future generations. The same reasoning applies here, since any utilitarian allocation characterized by some degree of intergenerational concern, $\Phi > 0$, will make the adult generation at time zero worse off (see Mourmouras, 1993; Valente, 2007).

The parameters and equilibrium values used in Figure 3 are reported in Table 1, where $g \equiv (Y_{t+1}/Y_t) - 1$ represents the net growth rate of output. Case I assumes relatively impatient consumers ($\beta = 0.55$ would correspond to a 3.3% average time-preference rate over 25 years). In this situation, even a unit social discount rate (i.e. each generation's welfare is weighted one half with respect to the previous generation) is compatible with positive growth rates, obtained via increased study time and reduced depletion rates. In Case II, agents are more willing to smooth consumption profiles ($\beta = 0.75$), and stronger spillover effects ($\psi = 1.62$) imply that the laissez-faire economy be closer to stationary output. Nonetheless, the utilitarian allocation yields strong growth effects, sustaining the economy even with heavier social discounting ($\rho = 2$). As shown in Figure 1, the first happy generation is that born in $t = 0$, in both cases.

Case	ρ	β	$\ell^\star$	ℓ^u	$z^\star$	z^u	ψ	$g^\star$	g^u
I	1.00	0.55	0.99	0.96	2.75	1.00	1.40	-7.6%	+8.2%
II	2.00	0.75	0.98	0.95	2.09	2.00	1.62	-0.5%	+4.6%
III	2.50	0.75	0.98	0.96	2.09	2.50	1.62	-0.5%	+0.6%

Table 1. Parameter and equilibrium values used in Figure 3

Resource-preservation effects are quite relevant for intergenerational welfare, since they increase the magnitude of the growth effects on which the mechanism of welfare-compensation hinges. Notice that Cases I and II display growth effects that hinge on both higher study time and reduced depletion rates ($\ell^u < \ell^\star$ and $z^u < z^\star$). If we assume higher discount rates, optimal policies are not R-preserving anymore, and growth effects are sensibly reduced, as shown in Table 1. In Case III, parameters are identical to Case II except for the social discount rate: setting $\rho = 2.5$ implies that the optimal policy be R-depleting - i.e. study time is higher than under laissez-faire, but natural capital declines faster ($z^u < z^\star$). As shown in Figure 3, g^u is still positive, but this is now exclusively due to increased rates of human capital formation in the social optimum, $\ell^u < \ell^\star$. The graphs on the

right show that the welfare-compensation effect is dramatically reduced: the first happy generation becomes that born in $t = 3$ - i.e. three generations lose their benefits, with respect to Case II.

3.3 Remarks

Our analysis emphasized the role of interactions between human and natural capital in resource-dependent economies. Studying these interactions is also relevant from an empirical perspective: in the last decade, a number of studies addressed the question of whether there is a fundamental relationship between resource dependence, income levels and output growth rates. Sachs and Warner (2001) argued that there is a negative relation between resource dependence and economic development, and labelled it as the 'curse of natural resources'. The existence of a resource curse was suggested by the poor growth performance of many countries that did not escape stagnation, despite great abundance of essential natural inputs, such as oil. Recent evidence suggests that the 'resource curse hypothesis' appears satisfied in countries where natural abundance is combined with weak institutions (Brunnschweiler, 2007) and low human capital (Gylfason, 2001). In the latter regard, an intuitive counterexample is represented by Scandinavian economies, where resource abundance did not generate 'Dutch-disease phenomena', but rather contributed to sustain development. Bravo-Ortega and De Gregorio (2005), and Stijns (2006) suggest that human capital formation has been a key discriminant between winners and losers: economies where workers are well-endowed with education and skills did not suffer from, but rather exploited resource abundance. Although this literature is not directly linked to the specific sustainability problem addressed here, the insights of our analysis appear consistent with empirical results. In particular, Bravo-Ortega and De Gregorio (2005) analyze data from Scandinavian and Latin American economies, and find a significant 'interaction term' between human capital and resource exploitation. This supports the idea that knowledge formation favors growth not only through direct effects, but also indirectly by reducing the rate of resources depletion. In our model, laissez-faire interactions crucially hinge on the functioning of intertemporal markets for resource assets: extending the analysis to consider alternative forms of transmission of property rights seems a promising way to obtain further insights on this point.

Another issue that deserves attention relates to the transition law of human capital. We have considered human capital as a knowledge stock which can be increased through study time, without modelling education regimes explicitly. Including monetary costs of education would represent an interesting extension

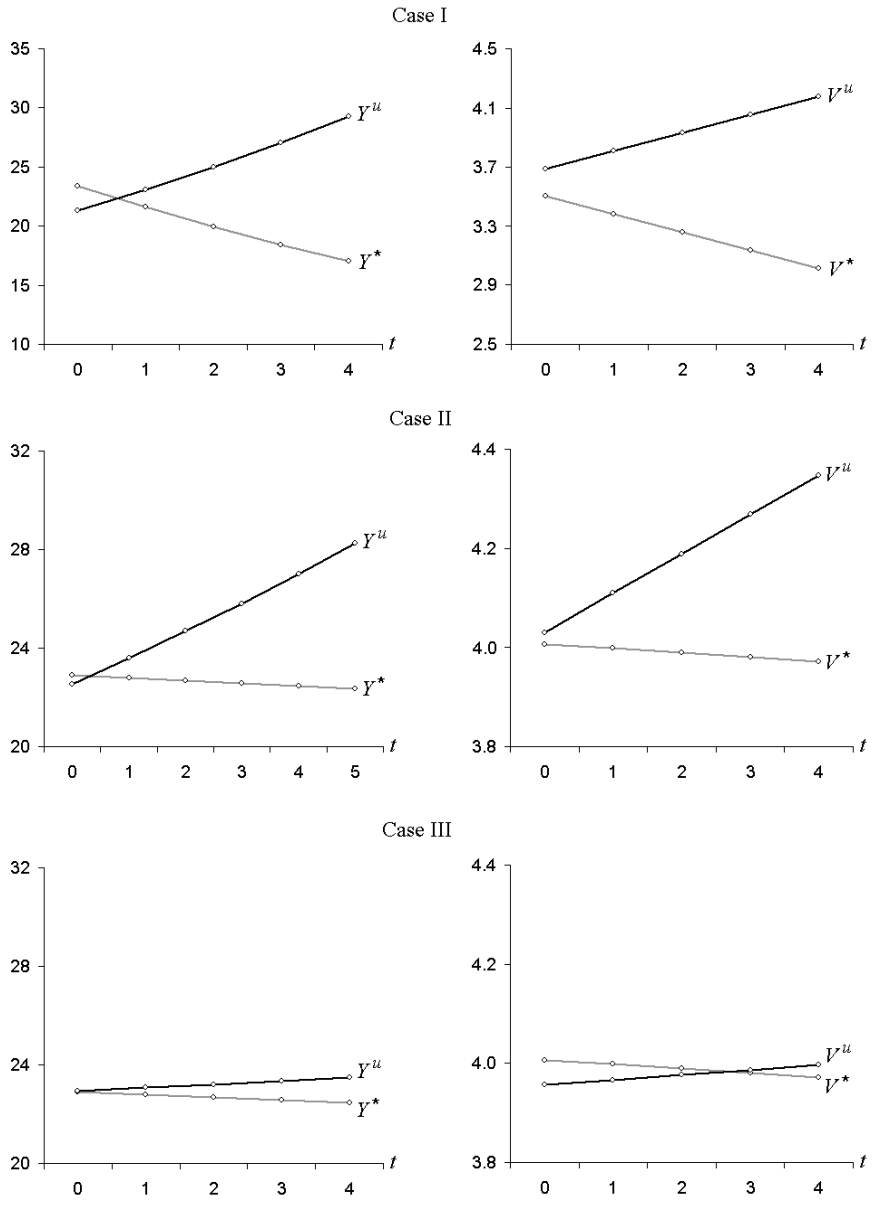

Figure 3: Output and welfare levels under laissez-faire versus utilitarian allocations. Parameter values are $\varepsilon = 0.02$ in case I, and $\varepsilon = 0.05$ in cases II and III, with $\alpha = 0.2$ in all cases.

from the perspective of both positive and normative analysis. The literature on human capital formation shows that educational expenditures have ambiguous effects on growth: depending on whether the economy favors private rather than public education systems, financing human capital formation may generate crowding-out or crowding-in effects on private wealth, and therefore positive or negative influence on economic growth (Blankenau and Simpson, 2004). As regards normative questions, when education is costly the optimal policy typically includes public expenditures that tend to raise education levels (Valente, 2005): the interaction between human capital and resource preservation will be obviously affected, but is difficult to say *a priori* in which direction. Comparing the effects of private versus public education regimes thus appears an interesting task for future research on sustainability issues.

4 Conclusions

The modern literature on sustainability follows two main approaches. Models of sustained growth emphasize the role of technological feasibility, and study the conditions for obtaining non-declining consumption in the presence of resource-augmenting innovations. The parallel literature on sustainable development focuses on the intertemporal distribution of resources, and study whether efficient allocation rules are compatible with intergenerational fairness. This paper merges the two frameworks in an endogenous growth model where human capital drives economic growth, and exhaustible resources are privately owned by overlapping generations of selfish agents.

In both laissez-faire equilibria and centrally-planned solutions, the rate of human capital accumulation is inversely correlated to the speed at which natural capital is depleted. In a competitive economy, enhanced knowledge formation reduces depletion rates by increasing the share of resources that present generations are willing to sell to successors. In the social optimum, human capital crowds out natural capital, but this is beneficial to growth: implementing utilitarian allocations implies a shift from unsustainable laissez-faire paths to sustainable and optimal paths, even for high rates of social discount. Knowledge formation and resource preservation are complementary targets because policies that raise study time must also reallocate resource entitlements across generations in order to be optimal. With respect to laissez-faire competitive equilibria, optimal solutions are generally knowledge-improving, but the rate of resource depletion may be higher or lower depending on the social discount rate. We have shown that growth effects are stronger when policies are resource-preserving, and that slackening depletion has relevant welfare implications. Due to the assumption of

overlapping generations, growth effects on output contrast the negative effects of redistribution in the short run. As a consequence, the achievement of welfare gains from optimal policies is delayed by faster depletion and, contrary to intuition, anticipated by lower social discount rates.

The positive correlation between study time and resource preservation is consistent with available empirical evidence, which suggests that resource-dependent countries exhibit good (bad) growth performance if natural abundance is (not) combined with fast growth in human capital. A first possible extension of the model relates to the accumulation law of human capital: we have ignored the effects of education expenditures, which may play an important role in determining both the size and the direction of crowding-out effects induced by knowledge accumulation. Second, the interaction mechanism behind the results hinges on the functioning of intertemporal markets for resource assets: in this regard, extending the analysis to consider alternative forms of intergenerational transmission of property rights seems a promising topic for further research on sustainability issues.

Appendix

Derivation of (53) and (54)

Substituting the intertemporal condition $e_{t+1}^{\star} = \beta c_t^{\star} i_{t+1}$ in individual preferences, lifetime utility in the laissez-faire equilibrium reads $V_t^{\star} = \log\left[\left(c_t^{\star}\right)^{1+\beta}\left(\beta i_{t+1}\right)^{\beta}\right]$. Substituting the implicit interest rate $i_{t+1} = \left(k_{t+1}^{\star}/k_t^{\star}\right)^{1-\alpha} = y_{t+1}^{\star}/y_t^{\star}$, and recalling that $y_{t+1}^{\star}/y_t^{\star} = \left(Y_{t+1}^{\star}/Y_t^{\star}\right)(1+z^{\star})$, we have

$$V_t^{\star} = \beta \log \beta \left[\psi\left(1-\ell^{\star}\right)^{\varepsilon}\left(1+z^{\star}\right)\right]^{1-\alpha} + (1+\beta)\log c_t^{\star}. \tag{55}$$

Substituting the budget constraint (9) in $c_t = e_{t+1}/\left(\beta i_{t+1}\right)$ yields

$$c_t = \frac{1}{\beta}\left(q_t a_t + \frac{w_{t+1}}{i_{t+1}} h_{t+1}\right) = \frac{1}{\beta}\left[q_t a_t + \frac{1}{\varepsilon} w_t\left(1-\ell_t\right) h_t\right],$$

where we have used $h_{t+1} = \varphi_t h_t$ and $\frac{w_{t+1}}{i_{t+1}} = \frac{w_t}{\varepsilon \varphi_t}\left(1-\ell_t\right)$. Using (6) and $a/X = n/z$ we can rewrite first-period consumption as

$$c_t = \frac{1}{\beta}\left[\frac{\alpha n}{z} + \left(\frac{1-\alpha}{\varepsilon}\right)\left(\frac{1-\ell_t}{1+\ell_t}\right)\right] Y_t,$$

which can be substituted in (55) to obtain expression (53) in the text, where we

have defined

$$\mathcal{F}'(\ell^\star, z^\star) \equiv \log\left\{\beta^\beta\left[\psi\left(1-\ell^\star\right)^\varepsilon\left(1+z^\star\right)\right]^{\beta(1-\alpha)}\left[\frac{\alpha n}{\beta z^\star}+\left(\frac{1-\alpha}{\beta\varepsilon}\right)\left(\frac{1-\ell^\star}{1+\ell^\star}\right)\right]^{(1+\beta)}\right\}.$$

As regards the utilitarian allocation, in the main text we have shown that consumption shares read $C_t/Y_t = \Phi(\beta+\Phi)^{-1}$ and $E_t/Y_t = \beta(\beta+\Phi)^{-1}$. Using these results and substituting $Y_{t+1}^u = (1+z^u)^{-\alpha}\psi^{1-\alpha}(1-\ell^u)^{\varepsilon(1-\alpha)}Y_t$, we obtain

$$V_t^u = \log\frac{\Phi}{n(\beta+\Phi)}\left[\left(\frac{\beta}{n(\beta+\Phi)}\right)\frac{\psi^{1-\alpha}(1-\ell^u)^{\varepsilon(1-\alpha)}}{(1+z^u)^\alpha}\right]^\beta + (1+\beta)\log Y_t^u. \quad (56)$$

Consolidating the first logarithm in $\mathcal{F}''(\ell^u, z^u)$ yields expression (54) in the text.

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