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Technological Progress, Time Perception, and Environmental Sustainability

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Abstract

This paper explores the relationship among technological progress, environment and growth by combining endogenous efficiency of public abatement with endogenous discounting. Our model can feature two different balanced growth paths corresponding to different levels of environmental quality, which remains constant in the long-run although the economy grows. The multiple equilibria point to a non-monotonic relationship among technological progress, growth and the environment, as observed in the data. A Ramsey planner can implement the good equilibrium; however, under a positive technology shock, the economy achieves higher long-run growth at the cost of lower environmental quality (even if agents value the environment highly). This finding could help us explain why some advanced economies may not succeed in cleaning the environment effectively.

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Keywords: Time preference, growth, environmental quality, fiscal policy, technological progress.

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1 Introduction

The link between economic growth and the environment is generally complex, and is often shaped by economic (notably fiscal) policy. It is well known that, across time, economic growth has a negative relation with environmental quality in the early stages of development, which tends to get reversed beyond a point (Grossman and Krueger, 1995; Millimet, List and Stengos, 2003; Varvarigos, 2014).[1] But across countries, advanced economies on average perform better in terms of growth and environmental quality, while developing countries often stagnate with low growth and low environmental quality (Fact 1). Interestingly, however, fast-growing economies could actually end up polluting the environment, ex post, despite there being increases in total factor productivity (TFP), which could have been utilised to finance pollution abatement (Fact 2).[2]

Using a unified framework, we attempt to explain those facts and examine the associated policy implications. First, we consider endogenous discounting of utility, which depends on environmental quality. A time-varying, rather than constant, discount rate is important for the evaluation of long-run projects, in particular when future generations are taken into consideration (Hepburn, Koundouri, Panopoulou and Pantelidis, 2009, and Freeman, Groom, Panopoulou and Pantelidis, 2015). In our case, better environmental quality increases the preferences for the future relative to the current period, raises savings and growth and, in turn, the resources to abate pollution activities. On the flip side, there exists a vicious cycle of high discount rate, low savings, low environmental quality and low growth. We take into account the factors that help us to explain Fact 1, which are about the existence of those two equilibria in a decentralized set-up; second, we consider endogenous (optimal) fiscal policy, which enables the 'bad' equilibrium (low growth and low environmental quality) to be eliminated. At the same time, we show that under increases in TFP, it is possible for some advanced economies

[1] An interesting observation made by Beckerman (1992) was that the "way to attain a decent environment in most countries is to become rich"!

[2] To provide a concrete example, if we take the case of China, although its income per capita and growth rate of output are much higher compared to the average values of the same for its neighbouring countries, China's environmental performance, as measured by the Environmental Performance Index (EPI), is at very similar levels to those countries (see Appendix A for details).

to perform badly in terms of the environment (while pursuing a welfare-maximizing policy), as this is illustrated by Fact 2.

In particular, we consider a competitive market with firms producing output using private and public capital. The latter could be interpreted as infrastructure, traditional or 'green'. Public capital is financed through income taxation to pay for the spending on infrastructure and abatement, as in Economides and Philippopoulos (2008), Ray Barman and Gupta (2010), Vella, Dioikitopoulos and Kalyvitis (2015). The stock of environmental quality, which evolves through time but remains constant in the long-run (Eliasson and Turnovsky, 2004), depends negatively on pollutants and positively on abatement expenditures, which are undertaken by governments to bring about improvements in environmental quality. This feature is present in a number of papers like Mohtadi (1996), Smulders and Gradus (1996), Byrne (1997), Liddle (2001), Bretschger and Smulders (2006), Managi (2006), among others.

Environmental degradation occurs via aggregate consumption, which is the source of pollution.[3] This is a realistic assumption, given that consumption of natural resources and the consumption of energy-intensive luxury goods are important sources of pollution. Consumption of automobile services (particularly when vehicles are without well-functioning catalytic converters) leads to significant air pollution. Household wastes and municipal sewage, when dumped into waterways, lead to widespread water pollution. Consumption of various electronic appliances leads to radiation and sound pollution. These are all by-products of consumption activities. Other examples include the consumption of fossil fuels like coal, wood, kerosene oil, etc., in the rural areas of developing countries. Some of the existing literature adopts this consumption-caused pollution hypothesis.[4] The dynamics of environmental quality, which is a function of pollution, evolve along the lines of Jouvet, Pestieau and Ponthiere (2010).

As regards environmental preservation, a distinct feature of our model is that the effective-

[3] This is in contrast to models that consider physical capital as the source of pollution: see, for example, Bovenberg and Smulders (1995), Elbasha and Roe (1996), Smulders and Gradus (1996), Byrne (1997), Cassou and Hamilton (2004), Benarroch and Weder (2006), Itaya (2008), Pautrel (2009), and Chu, Lai and Liao (2015).

[4] See the contributions of John and Pecchenino (1994), Howarth (1996), Liddle (2001), Egli and Steger (2007), Quaas (2007), Bertinelli, Strobl and Zou (2008), Gupta and Ray Barman (2009), etc. In Bretschger and Smulders (2006), pollution is modelled as a by-product of either capital or consumption, while in the recent paper by Michael, Lahiri and Hatzipanayotou (2015), pollution is generated via both production and consumption.

ness of public abatement expenditure is enhanced by the amount of infrastructure per unit of output.[5] To this end, one can cite examples of investment in green infrastructure projects, e.g., efficient management of stormwater, climate adaptation and provision of green space, which can supplement the direct benefits from abatement.[6] Public spending on human capital accumulation that could enable the educated to carry out R&D activities to bolster the environment is yet another example of this phenomenon.

We consider, first, the workings of a decentralized economy where the government takes the tax rate and the proportion of spending on infrastructure vis-a-vis abatement as given, and then the case of a benevolent government that formulates its fiscal policy optimally (i.e., chooses its instruments: the tax rate and the proportion of spending on abatement to maximize agents' welfare. The latter case of an optimizing government is one where the Ramsey fiscal policy is pursued to attain the second-best scenario.

Our results for the decentralized economy show, interestingly, that there emerge multiple (two) equilibria: one, a 'bad', low-growth, equilibrium, and the other, a 'good', high-growth, equilibrium. The former typifies the case of a resource-poor country, with consumers having a high degree of impatience and high consumption propensity, which, in addition to low growth also results in high pollution and low environmental quality. Exactly the opposite holds for the other equilibrium, the prototype of an advanced economy, characterized by a low rate of time preference, low consumption-to-capital ratio, low pollution, good environmental quality and high growth. Our findings can be compared with Schumacher (2009) where multiplicity of steady states occurs since when an agent is very poor, then increases in consumption are necessary for survival, and the agent is so impatient that the preferences are clearly directed towards the current period. By contrast, when overall wealth has already been built up sufficiently, the

[5]Governments finance a variety of enviornmental protection activities (public abatement). The proportion of government expenditure in total expenditure on abatement is relatively high in many countries (see e.g. Hatzipanayotou, Michael and Lahiri, 2003, and Haibara, 2009).

[6]See Quaas (2007) for a spatial equilibrium model of an economy - based on stylized facts observed for the city of Bombay in India - where the harmful consequences of environmental pollution, generated as by-product of consumption, may be reduced by supplying adequate infrastructure (like proper sewage systems, public sanitation and waste disposal facilities, paved roads, etc.).

discount rate becomes relatively low and people plan ahead for the future.[7] We also study the implications of higher TFP for both equilibria. For the bad equilibrium, despite the higher output, consumption rises more than in proportion, pollution is higher and environmental quality is lower; the resulting higher degree of impatience contributes to even lower growth.

Under Ramsey fiscal policy, by contrast, we no longer have the existence of two feasible equilibria, but end up with only one equilibrium. The government, by being able to exercise two additional instruments, other than its overall expenditure, is able to channel the economy in a direction whereby it can avoid being trapped in the bad equilibrium, so only the high-growth equilibrium (with good environmental quality) ensures. The implications of technological progress in this case is to achieve higher output and thereby to strive for ever higher rates of growth by allocating a higher proportion of government revenues towards infrastructure, even if this 'dynamic' objective comes at the cost of some lowering of environmental quality.[8]

The contribution of our paper is, therefore, threefold. First, it extends the existing literature on growth, environment and endogenous discounting by providing a unified environmental law of motion, and taking into account the effect of 'green' infrastructure on the efficiency of abatement technology. As distinct from Yanase (2011), in our model environment evolves as stock, which is more realistic, and this enables us to capture the empirical fact of the existence of an environmental poverty trap. Also, differently to Vella, Dioikitopoulos and Kalyvitis (2015), here time preference depends solely on environmental quality, while consumption adds negatively to environmental preservation. This feature of our model enables us to focus on the sole effect of environmental quality on time discounting.

Second, we provide an explanation for the poor environmental performance of advanced countries through a normative aspect (endogenous government policy) by bringing forward the

[7] By contrast, in Chu, Lai and Liao (2015), despite time preference being endogenous, the decentralised equilibrium is unique and locally determinate, and there are no transitional dynamics (and the same is true of the social optimum).

[8] In Economides and Philippopoulos (2008), when citizens care more about the environment, extra revenues for abatement need to be generated through a higher tax rate and tax base (i.e., higher growth), which is what a Ramsey policymaker implements: so there is no incompatibility between growth-maximising and environment-friendly policies. However, in their model, renewable resources grow at the same positive rate as that of output, which is not the case here.

link with TFP. While other models tried to explain the fact the advanced economies have better performance in terms of envronmental quality, to the best of our knowledge, this is the first paper that shows that under a second-best welfare maximizing policy objective, advanced countries could end up hurting the environment.

Third, our paper contributes to the literature on endogenous growth and environmental resources by developing a model in which balanced growth is consistent with constant environmental quality, under explicit modelling of environmental dynamics and fiscal policy. Notably, unlike Vella, Dioikitopoulos and Kalyvitis (2015), the two balanced growth paths are associated with different levels of (constant) environmental quality. Also, Eliasson and Turnovsky (2004) have emphasized the shortcomings of existing endogenous growth models in generating a constant level of environmental quality in the long-run. They, however, use a simpler framework that does not consider public environmental policies.

Turning now to real world data, although various trends can be observed our results go some way towards explaining the situation in high-growth economies like China over the past decade, where a rise in productivity, higher investment in infrastructure and high growth rates exist side by side with some decline in the quality of the environment. More specifically, for China, research and development (R&D) expenditure (as % of GDP) rose continuously over the years (from 1.32 in 2005 to 1.98 in 2012).[9] With a decadal growth rate of 10% and GDP per capita (in current US$) that rose from 1,731.1 in 2005 to 6,807.4 in 2013, a decline in environmental quality was evident as regard emissions of CO_2, methane and N2O. CO2 emissions, for example, went up from 4.4 in 2005 to 6.2 in 2010. In line with the research conducted in this study, the data from China indicates that policy-induced changes have had an effect on growth and the environment, with the improvement in technology boosting growth but depleting the environment to an extent.[10]

[9] If, instead of R&D expenditure, we considered other items listed under the "Science & Technology" indicator, such as researchers in R&D (per million people), then also it can be seen that there was an increase (from 890 in 2010 to 1020 in 2012). Yet another indicator: patent applications (residents), shows the same trend, with such applications increasing about 2.5 times between 2010 and 2013 in China. For India, too, we see a similar trend for this indicator.

[10] It is more appropriate to link these trends in the data to the Ramsey policy outcome rather than to a pure EKC effect (where a decline in environmental quality occurs with higher economic growth) because countries

The rest of the paper is structured as follows. Section 2 sets up the model. Section 3 solves the optimization problem of households and firms, and studies the properties of the decentralized economy. Section 4 analyzes the role of Ramsey government in selecting a second-best allocation and studies the effect of technological progress on policy instruments. Finally, section 5 concludes the paper.

2 The model

This section presents the set-up of our closed-economy model. The main features are as follows: (a) households derive utility from consumption and environmental quality, which has a public good character; (b) the subjective discount rate is a negative function of environmental quality, taken as given by the agents; (c) public infrastructure provides production externalities to firms and enhances the efficiency of abatement technology; (d) consumption generates environmental pollution; (e) the government imposes a tax on output and uses the collected tax revenues to finance infrastructure and abatement.

2.1 Households

The economy is made up of a large number of identical, infinitely-lived households, normalized to unity, and each one seeks to maximize the present discounted value of the lifetime utility:

$$\int_0^{\infty} u(C_t, N_t) \exp\left[-\int_0^t \rho(N_v) dv\right] dt \tag{1}$$

where $u(C, N) = v \ln C + (1 - v) \ln N$ is the instantaneous utility function with $0 < v \leq 1$ measuring how much agents value consumption, C, vis-à-vis the stock of economy-wide natural resources, interpreted as an index for environmental quality, N. In turn, $\rho(N)$ denotes the endogenous rate of time preference (RTP), which is assumed to depend negatively on environ-

like China (and India to a somewhat lesser extent) can be viewed as economies that are to the right of the turning point of the Kuznets curve to start with, and so any adverse effect on the environment is likely to be an outcome of policy that focuses more single-mindedly on growth than on some other objectives.

mental quality, i.e. $\rho_N \leq 0$.[11] The assumption, that a higher level of environmental quality lowers individual impatience, follows Yanase (2011) and captures the well-documented 'life expectancy effect' of environmental quality or pollution (see Introduction). Further, we assume that there exists a lower positive bound for the RTP, denoted by $\breve{\rho}$, i.e. $\lim_{(N)\to 0} \rho(N) = \breve{\rho} > 0$.

Households save in the form of capital and receive dividends, π. The budget constraint of the household is given by:

$$\dot{W} + C = rW + \pi \tag{2}$$

where a dot over a variable denotes a derivative with respect to time, r is the capital rental rate, W denotes financial assets and the initial asset endowment $W(0) > 0$ is given. The household acts competitively by taking prices, policy, and environmental quality as given. The latter is justified by the open-access and public good features of the environment. The control variables are the paths of C and W, so that the first-order conditions include the constraint (2) and the Euler equation below:

$$\frac{\dot{C}}{C} = r - \rho(N) \tag{3}$$

Notice that environmental quality affects consumption growth positively through the RTP, and thus plays an implicit 'productive' role in the economy.

2.2 Firms

The production function of the single good in this economy is given by:

$$Y = AK^a {K_g}^{1-a} \tag{4}$$

where Y denotes output, $0 < a < 1$ denotes the share of physical capital, K, in the production function, K_g refers to the public capital stock (e.g. infrastructure) and A represents TFP. Labour endowment is normalized to unity as we assume no population growth.[12] The law of

[11] We retain the equality sign to allow for comparisons with the case of constant RTP.

[12] This specification follows the strand of endogenous growth theory assuming that the government can invest in productive public capital, which will stimulate aggregate productivity (see e.g., Barro, 1990; Futagami, Morita

motion for the public capital stock is given by:

$$\dot{K}_g = G - \delta_{K_g} K_g \tag{5}$$

where δ_{K_g} denotes the depreciation rate and G is government investment in public capital. The initial capital stock $K_g(0) > 0$ is given. The firm maximizes profits, π:

$$\pi = (1-\tau)Y - (r + \delta_K)K \tag{6}$$

where $0 < \tau < 1$ is a tax rate on output, δ_K is the depreciation rate of private capital, and its summation with r forms the rental cost of capital. The firm acts competitively by taking prices and policy instruments as given. The first-order condition equates the marginal productivity of capital to its rental cost:

$$r + \delta_k = Aa(1-\tau)\left(\frac{K}{K_g}\right)^{a-1} \tag{7}$$

2.3 Motion of environmental quality

Following Jouvet, Pestieau and Ponthiere (2010), we assume that the stock of environmental quality evolves over time according to:

$$\dot{N} = (1-\delta_N)\bar{N} - (1-\delta_N)N - D \tag{8}$$

where $\bar{N}$ denotes environmental quality without degradation, D, and $\delta_N \in (0,1)$ is the degree of environmental persistence. The initial stock $N(0) > 0$ is given.

Environmental degradation, D, is a positive function of pollution emissions, P, and a negative function of public abatement expenditures, E, i.e. $D_P(P,E) > 0$ and $D_E(P,E) < 0$:

$$D = D(P,E) = \frac{P}{\theta E} \tag{9}$$

and Shibata, 1993).

where $0 < \theta \leq 1$ denotes the efficiency of the abatement technology in alleviating environmental degradation.[13]

We further assume that P occurs as a by-product of consumption:

$$P = sC \tag{10}$$

where $0 < s < 1$ is a parameter that quantifies the detrimental effect of consumption on the environment.[14]

In the same vein as Andreoni and Levinson (2001), we assume that the efficiency of expenditures to abate the environment depend on the size of the economy and the level of infrastructure. In particular, we assume that the efficiency of abatement technology is a positive function of infrastructure stock as a share of total output, $\frac{K_g}{Y}$:

$$\theta = \theta\left(\frac{K_g}{Y}\right) = \xi \frac{K_g}{Y} \tag{11}$$

where $\xi > 0$ is the parameter that captures the effect of infrastructure on the efficiency of abatement. Intuitively, higher public investment on activities pertaining to public infrastructure complements public expenditures on abatement and makes it possible to clean the environment in a more efficient way. To take some concrete examples of this, let us consider effective stormwater management. This involves providing drainage support in urban areas, as without such efforts, water does not infiltrate the ground due to much of the surface being impervious, and causes pollution and flooding via runoffs.[15] One can also consider public spending on education as a public capital good that affects production and at the same time complements

[13]For papers with publicly financed abatement see e.g. Ligthart and van der Ploeg, 1994; Greiner, 2005; Pérez and Ruiz, 2007; Gupta and Barman, 2010; Vella, Dioikitopoulos and Kalyvitis (2015). An interesting extension for future research would be to model both private and public abatement.

[14]As in Andreoni and Levinson (2001), Egli and Steger (2007), Gupta and Ray Barman (2009), Mariani, Perez-Barahona and Raffin (2010), and Michael, Lahiri and Hatzipanayotou (2015), we consider a linear relationship between pollution flows and consumption activities for the sake of simplicity.

[15]For example, permeable pavements in parks and parking lots, and wetlands for management of stormwater runoff, have been constructed in the US city of Philadelphia. Also, in Singapore, stormwater runoff is treated without the use of chemicals but naturally, through the use of plants and soil media, so that cleaner water is discharged into waterways and eventually to reservoirs.

the abatement efficiency. Such publicly funded education would be expected to make people intelligent enough to create more technologies to clean the environment, resulting in a unit spending on abatement to generate even greater benefits. As another example, consider public spending on transport infrastructure. We know that the conditions of roads are adversely affected by acid rain (potholes and cracks develop periodically). If the government spends to maintain such roads (and even spends on new roads), while at the same time spending on abatement (i.e., spending on research to tackle the causes of acid rain and lessen its harmful effects), then better quality roads will mean less corrosive effect of acid rain on roads, so a unit of spending on abatement will be more efficient. Likewise, higher public spending on health infrastructure (by increasing hospitals and improving hospital services), if undertaken simultaneously with abatement spending to tackle air pollutants (like benzene and butadiene, which could cause long-term health problems like cancer and cardio-vascular diseases), then people's health, and therefore their capacity to withstand the harmful effects of pollutants, will improve, so again it supplements the direct benefits of abatement expenditure. In all these examples, spending on public infrastructure are complements to abatement expenditures that tackle environmental problems directly. The negative effect of income comes from congestion effects on public investment (see Turnovsky, 2000).

2.4 Government budget constraint

The government spends G on infrastructure and E on environmental policy, and collects revenues through a tax on output, $0 < \tau < 1$. Assuming a balanced budget, we can write:

$$G + E = \tau Y \tag{12}$$

Equivalently, (12) can be written as:

$$G = b\tau Y \tag{13}$$

$$E = (1 - b)\tau Y \tag{14}$$

where $0 < b < 1$ is the fraction of tax revenue used to finance infrastructure and $0 < (1-b) < 1$ is the fraction that finances environmental investment. Thus, government policy can be summarized by the two policy instruments, τ and b.

3 Decentralized competitive equilibrium

In this section we solve for a DCE, which holds for any feasible policy, and analyze its properties.

Definition 1 *The DCE of the economy is defined for the exogenous policy instruments τ and b, the factor price r, and the aggregate allocations K, K_g, N, G, E, C such that:*

i) Individuals solve their intertemporal utility maximization problem by choosing c and W, given the policy instruments and the factor price.

ii) Firms choose K in order to maximize their profits, given the factor price and aggregate allocations.

iii) All markets clear, which implies for the capital market $W = K$ (assets held by agents equal the private capital stock).

iv) The government budget constraint holds.

Combining (1)-(14) and assuming for the rest of the paper, without loss of generality, that $\delta_K = \delta_{K_g} = \delta$, it is straightforward to show that the DCE is given by:

$$\frac{\dot{C}}{C} = \left[Aa(1-\tau)\left(\frac{K}{K_g}\right)^{a-1} - \delta - \rho\left(N\right) \right] \tag{15}$$

$$\frac{\dot{K}}{K} = A(1-\tau)\left(\frac{K}{K_g}\right)^{a-1} - \frac{C}{K} - \delta \tag{16}$$

$$\frac{\dot{K}_g}{K_g} = Ab\tau\left(\frac{K}{K_g}\right)^{a} - \delta \tag{17}$$

$$\dot{N} = (1-\delta_N)\bar{N} - (1-\delta_N)N - \left(\frac{s}{\xi(1-b)\tau}\frac{C}{K_g}\right) \tag{18}$$

Equations (15)-(18) summarize the dynamics of the economy. Owing to the presence of environmental quality in (15), equations (15)-(17) cannot be solved independently of (18).

Finally, the transversality condition for this problem is given by:

$$\lim_{t\to\infty} \frac{K(t)}{C(t)} \exp\left[-\int_0^t \rho\left(N_s\right) ds\right] = 0 \tag{19}$$

The balanced growth path (BGP) in this economy is defined as a state where variables C, K, K_g, Y grow at a constant rate, g, and environmental quality is constant. Following usual practice, we will reduce dimensionality to facilitate analytical tractability by defining the following auxiliary stationary variables, $\omega \equiv \frac{C}{K}$ and $z \equiv \frac{K}{K_g}$. Then, it is straightforward to show that the dynamics of (15)-(18) are equivalent to the dynamics of the following system of equations:

$$\frac{\dot{\omega}}{\omega} = A(a-1)(1-\tau)z^{a-1} - \rho\left(N\right) + \omega \tag{20}$$

$$\frac{\dot{z}}{z} = A(1-\tau)z^{a-1} - Ab\tau z^{a} - \omega \tag{21}$$

$$\dot{N} = (1-\delta_N)\bar{N} - (1-\delta_N)N - \left(\frac{s}{\xi(1-b)\tau}\omega z\right) \tag{22}$$

It follows that at the BGP $\frac{\dot{\omega}}{\omega} = \frac{\dot{z}}{z} = \frac{\dot{N}}{N} = 0$.[16] Then (21) implies that the long-run ratio of consumption to private capital, $\hat{\omega}$, is expressed as a function of the long-run ratio of private capital to public capital, $\hat{z}$, by:

$$\hat{\omega}(\hat{z}) = A(1-\tau)\hat{z}^{a-1} - Ab\tau\hat{z}^{a} \tag{23}$$

and (22) implies that the long-run value for environmental quality is given by:

$$\hat{N}(\hat{z}) = \bar{N} - \Xi[(1-\tau)A\hat{z}^{a} - b\tau A\hat{z}^{a+1}] \tag{24}$$

[16] In our paper, we have constant growth of consumption, capital (private and public) and output in a steady state but, by contrast, environmental quality remains constant. The latter feature is not present in Economides and Philippopoulos (2008), or in Vella, Dioikitopoulos and Kalyvitis (2015).

where $\Xi(b,\tau;\delta_N,s) \equiv \frac{s}{(1-\delta_N)\xi(1-b)\tau}$.

Substituting then (23)-(24) in (20), given that $\frac{\dot{N}}{N}=0$, we get that $\hat{z}$ is determined by:

$$\Phi(\hat{z}) \equiv -Ab\tau\hat{z}^a + Aa(1-\tau)\hat{z}^{a-1} - \rho(\bar{N} - \Xi[(1-\tau)A\hat{z}^a - b\tau A\hat{z}^{a+1}]) = 0 \tag{25}$$

Providing there exists a solution $\hat{z} > 0$ in (25), the balanced growth rate, g, is then determined by (17).

Assuming equilibrium existence, equations (23)-(25) imply the following:

Proposition 1 *Endogenous efficiency of abatement technology in public capital and endogenous subjective discount rate in environmental quality can lead to multiple long-run growth equilibria. In particular,*

Case 1 (Uniqueness): if $Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^a < \check{\rho}$ *then the equilibrium is unique*

Case 2 (Multiplicity): if $Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^a > \check{\rho}$ *then there can be two equilibria, associated with different growth rates ranked* $g_1 > g_2$ *where* $\rho_1 < \rho_2$, $\hat{\omega}_1 < \hat{\omega}_2$, $\hat{z}_1 > \hat{z}_2$.

Proof. See Appendix. ∎

Proposition 1 states that endogenous time preference to environmental quality and endogenous efficiency of public abatement to infrastructure spending can lead to multiple solutions for $\hat{z}$, and, in turn, multiple equilibria in the competitive decentralized equilibrium.[17] In particular, in the long-run equilibrium with high growth, g_1, the rate of time preference is lower, $\rho_1 < \rho_2$, the consumption-to-physical-capital ratio is lower, $\hat{\omega}_1 < \hat{\omega}_2$, and the physical-to-public-capital ratio is higher, $\hat{z}_1 > \hat{z}_2$. Hence, although the instantaneous utility and production technology functions satisfy the standard concavity assumptions, the existence of a unique positive balanced growth rate is not guaranteed here.

In particular, our model solves for two equilibria: a low-(high-) growth one with low (high) environmental quality, a high (low) rate of time preference, a high (low) consumption-capital ratio and a low (high) physical-to-public capital ratio. This reflects the characteristics of a 'self-defeating' ('self-fulfilling') equilibrium that results from our model set-up. In the former case, a

[17] We have checked that both equilibria are stable. Results are available upon request.

typically poor economy, the propensity to consume is larger, and this generates more pollution (a by-product of c) and a lower environmental quality. This, and the higher consumption propensity, ties in with a high value for the degree of impatience, a higher $\hat{\omega}$ ratio, and a lower $\hat{z}$ ratio. The higher degree of impatience in turn leads to a lower growth, which is self-defeating in the sense that a kind of vicious cycle of lower environmental quality and low growth propagates to keep the economy in a 'low-level equilibrium trap' situation. On the other hand, in the other kind of economy (which is rich), lower consumption propensity, better environmental quality and lower impatience combine to deliver a high-growth outcome, which is self-sustaining.

3.1 Technological progress, environmental quality and growth

In this sub-section, we study the effect of a change in technological progress, as given by an increase in TFP, on environmental quality and growth. Given the complexity of the system, we resort to numerical simulations, using the parameterization reported in Table A. The values of the economic parameters are as in most dynamic general equilibrium calibration and estimation studies.

The values used for the productivity of private capital in the production function, α, and the capital depreciation rate, δ, come from Economides and Philippopoulos (2008) and Dioikitopoulos and Kalyvitis (2010). Following common practice, we use the TFP, A, as a scale parameter to help us get plausible values for the growth rates. We set the values for the detrimental effect of consumption on the environment, s, and the exogenous effectiveness of environmental policy, ξ, following Economides and Philippopoulos (2008), while for the regeneration rate of natural resources, δ_N, we use a value that is sufficiently high to ensure a non-negative growth rate for the environmental stock. We employ a linear time preference function, $\rho(N) = -\gamma \times (N) + \breve{\rho}$, $\gamma > 0$, for computational tractability (see, e.g., Pittel, 2002; Dioikitopoulos and Kalyvitis, 2010), which is rich enough to obtain our main results. The chosen values for the lower bound, $\breve{\rho}$, and slope, γ, help us calibrate values for ρ in line with the literature. In particular, the highest RTP values reported for the low-growth regime are close to that in Elbasha and Roe

(1996), while those reported for the high-growth regime are in the range commonly employed in the growth literature.

Table 1. Technological Progress, Growth and the Environment

A	$\hat{z}_1$	$\hat{z}_2$	$\hat{\omega}_1$	$\hat{\omega}_2$	$\hat{N}_1$	$\hat{N}_2$	$\hat{\rho}_1$	$\hat{\rho}_2$	g_1	g_2
1	0.5994	0.6172	0.4788	0.4651	0.1252	0.1258	0.1221	0.1135	0.2097	0.2132
1.01	0.5120	0.7100	0.5608	0.4042	0.1219	0.1285	0.1708	0.0731	0.1941	0.2330
1.02	0.4746	0.7526	0.6049	0.3813	0.1203	0.1296	0.1959	0.0565	0.1880	0.2432
1.03	0.4470	0.7853	0.6423	0.3654	0.1189	0.1304	0.2168	0.0443	0.1838	0.2517
1.04	0.4245	0.8129	0.6764	0.3530	0.1176	0.1310	0.2355	0.0344	0.1804	0.2592
1.05	0.4052	0.8371	0.7085	0.3427	0.1164	0.1316	0.2529	0.025	0.1776	0.2662

A higher value of A, representing technological progress in an economy, typically raises output. In an economy characterized by a low level of environmental quality, and in turn less patience and lower propensity to save, an increase in output raises consumption proportionately more than private saving and causes more pollution and worsens environmental quality. A slowly growing economy will also end up with a low tax base, and will have lower resources to allocate to both infrastructure and abatement, so that the environmental quality deteriorates further, raising the degree of impatience and giving rise to a further growth-reducing effect. Exactly the opposite happens to the high-growth equilibrium, which experiences less pollution, better environmental quality, lower degree of impatience and higher growth. Table 1 provides a numerical example to substantiate this theoretical result.

Result 1 *An increase in TFP negatively affects environmental quality and growth in relatively poor economies and positively affects environmental quality and growth in relatively rich economies.*

4 Ramsey fiscal policy

In this section we endogenize fiscal policy, as summarized by the time paths of the two policy instruments, $0 < \tau < 1$ and $0 < b \leq 1$, by solving for the Ramsey second-best problem of the government. Given a welfare criterion that the government uses to evaluate different allocations, the Ramsey problem for the government is to pick the fiscal policy that generates the competitive equilibrium allocation with the highest value of this criterion.[18]

Definition 2 *A Ramsey Allocation is given under Definition 1 when (i) the government chooses the tax rate, τ, and the allocation of revenues to infrastructure and public abatement, b, in order to maximize the welfare of the economy by taking into account the aggregate optimality conditions of the competitive equilibrium, and (ii) the government budget constraints and the feasibility and technological conditions are met.*

In particular, the government seeks to maximize welfare in the economy subject to the outcome of the decentralized equilibrium, summarized by (15)-(18). Due to the variable RTP, Pontryagin's maximum principle cannot be applied directly. To solve the problem within the standard optimal control framework, we follow the procedure employed by Obstfeld (1990) and introduce an additional 'artificial' variable that accounts for the development of the accumulated discount rate, $\Delta(t) \equiv \int_0^t \rho(N_v)dv$. Then, the objective of the government is to maximize intertemporal utility:

$$\max U^R = \int_0^{\infty} (v \ln C + (1-v)\ln N) \exp\left[-\int_0^t \rho(N)dv\right] dt$$

constrained by the competitive equilibrium, (15)-(18), and the derivative of $\Delta(t)$ with respect to time, $\dot{\Delta} = \rho(\cdot)$.

The Hamiltonian of the problem is given by:

$$\begin{aligned} \Lambda^{RSB} &= [\nu \log C + (1-\nu)\log(N)]e^{-\Delta} + \lambda_C C[a(1-\tau)A\left(\frac{K}{K_g}\right)^{a-1} - \delta - \rho(N)] \\ &\quad + \lambda_K\left[(1-\tau)AK^aK_g^{1-a} - C - \delta K\right] + \lambda_{K_g}\left(b\tau AK^aK_g^{1-a} - \delta K_g\right) \\ &\quad + \lambda_N\left[(1-\delta_N)\bar{N} - (1-\delta_N)N - \frac{\psi}{\xi(1-b)\tau}\frac{C}{K_g}\right] + \lambda_\Delta \rho(N) \end{aligned}$$

[18] For second-best policies in models with environmental resources, see e.g Antoniou, Hatzipanayotou and Koundouri (2012) and Economides and Philippopoulos (2008).

The first-order conditions of the Ramsey problem include the Euler equation, the growth rates of private capital, public capital and environmental quality, the resource constraint, and the optimality conditions with respect to C, K_g, K, N, τ, b, Δ:

$$\frac{\nu}{C}e^{-\Delta} + \lambda_C\left[Aa(1-\tau)\left(\frac{K}{K_g}\right)^{a-1} - \delta - \rho\left(N\right)\right] - \lambda_K - \lambda_N\frac{\psi}{\xi(1-b)\tau}\frac{1}{K_g} = -\dot{\lambda}_C \tag{26}$$

$$\lambda_C C\left[Aa(1-\tau)\left(a-1\right)K^{a-2}K_g^{1-\alpha}\right] + \lambda_K\left[A(1-\tau)\alpha\left(\frac{K}{K_g}\right)^{a-1} - \delta\right] + \lambda_{K_g}Ab\tau\alpha\left(\frac{K}{K_g}\right)^{a-1} = -\dot{\lambda}_K \tag{27}$$

$$\lambda_C C\left[Aa(1-\tau)\left(1-\alpha\right)K^{a-1}K_g^{-\alpha}\right] + \lambda_K(1-\tau)\left(1-\alpha\right)A\left(\frac{K}{K_g}\right)^{a} + \lambda_{K_g}\left[b\tau\left(1-\alpha\right)A\left(\frac{K}{K_g}\right)^{a} - \delta\right] + \lambda_N\frac{\psi}{\xi(1-b)\tau}\frac{C}{K_g^2} = -\dot{\lambda}_{K_g} \tag{28}$$

$$\frac{(1-\nu)}{N}e^{-\Delta} - \lambda_C C\rho'(N) - \lambda_N(1-\delta_N) + \lambda_\Delta\rho'(N) = -\dot{\lambda}_N \tag{29}$$

$$\lambda_C C\left[-aA\left(\frac{K}{K_g}\right)^{a-1}\right] - \lambda_K AK^aK_g^{1-a} + \lambda_{K_g}AbK^aK_g^{1-a} + \lambda_N\frac{\psi}{\xi(1-b)\tau^2}\frac{C}{K_g} = 0 \tag{30}$$

$$\lambda_{K_g}\tau AK^aK_g^{1-a} - \lambda_N\frac{\psi}{\xi(1-b)^2\tau}\frac{C}{K_g} = 0 \tag{31}$$

$$[\nu\log C + (1-\nu)\log N]e^{-\Delta} = \dot{\lambda}_\Delta \tag{32}$$

where $\lambda_C, \lambda_K, \lambda_{K_g}, \lambda_N, \lambda_\Delta$ are the dynamic multipliers associated with (26), (27), (28), (29). Then, condition $\dot{\Delta} = \rho(\cdot)$ and equations (26)-(32) characterize the dynamics of the Ramsey problem. To obtain the long-run solution of the problem we define the stationary variables: $\omega \equiv \frac{C}{K}$, $z \equiv \frac{K}{Kg}$, $c \equiv \tilde{\lambda}_C C$, $\kappa \equiv \tilde{\lambda}_K K$, $\kappa_g \equiv \tilde{\lambda}_{K_g}K_g$ where $\tilde{\lambda}_i = e^{\Delta}\lambda_i$. After some algebra the long-run Ramsey equilibrium is given by:

$$\nu + \tilde{c}\left[Aa(1-\tilde{\tau})\tilde{z}^{a-1} - \delta - \rho\left(\tilde{N}\right)\right] - \tilde{\kappa}\tilde{\omega} - \tilde{\lambda}_N\frac{\psi}{\xi(1-\tilde{b})\tilde{\tau}}\tilde{\omega}\tilde{z} = (A\tilde{b}\tilde{\tau}\tilde{z}^a - \delta)\tilde{c} + \tilde{\rho}(\tilde{N})\tilde{c} \tag{33}$$

$$\tilde{\rho}(\tilde{N}) = -\gamma\tilde{N} + \breve{\rho} \tag{34}$$

$$\tilde{c}a(1-\tilde{\tau})\,(a-1)\,A\tilde{z}^{a-1} + \tilde{\kappa}\left[(1-\tilde{\tau})A\alpha\tilde{z}^{a-1} - \delta\right] + \tilde{\kappa}_g A\tilde{b}\tilde{\tau}\alpha\tilde{z}^a = (A\tilde{b}\tilde{\tau}\tilde{z}^a - \delta)\tilde{\kappa} + \tilde{\rho}(\tilde{N})\tilde{\kappa} \tag{35}$$

$$\begin{aligned}\tilde{c}\left[Aa(1-\tilde{\tau})\,(1-\alpha)\,\tilde{z}^{a-1}\right] &+ \tilde{\kappa}A(1-\tilde{\tau})\,(1-\alpha)\,\tilde{z}^{a-1}\\ &+ \tilde{\kappa}_g\left[A\tilde{b}\tilde{\tau}\,(1-\alpha)\,\tilde{z}^a - \delta\right] + \tilde{\lambda}_N\frac{\psi}{\xi(1-\tilde{b})\tilde{\tau}}\tilde{\omega}\tilde{z} = (A\tilde{b}\tilde{\tau}\tilde{z}^a - \delta)\tilde{\kappa}_g + \tilde{\rho}(\tilde{N})\tilde{\kappa}_g\end{aligned} \tag{36}$$

$$\tilde{c}\left[-aA\tilde{z}^{a-1}\right] - \tilde{\kappa}A\tilde{z}^{a-1} + \tilde{\kappa}_g A\tilde{b}\tilde{z}^a + \tilde{\lambda}_N\frac{\psi\tilde{\omega}\tilde{z}}{\xi(1-\tilde{b})\tilde{\tau}^2} = 0 \tag{37}$$

$$(1-\nu) - \tilde{c}\tilde{\rho}'(\tilde{N})\tilde{N} - \tilde{\lambda}_N\tilde{N}(1-\delta_N) - \tilde{\rho}(\tilde{N})\lambda_N\tilde{N} = 0 \tag{38}$$

$$A\tilde{\kappa}_g\tilde{\tau}\tilde{z}^a - \tilde{\lambda}_N\frac{\psi\tilde{\omega}\tilde{z}}{\xi(1-\tilde{b})^2\tilde{\tau}} = 0 \tag{39}$$

$$A(a-1)(1-\tilde{\tau})\tilde{z}^{a-1} - \tilde{\rho}\,(N) + \tilde{\omega} \tag{40}$$

$$\tilde{\omega} = A(1-\tilde{\tau})\tilde{z}^{a-1} - A\tilde{b}\tilde{\tau}\tilde{z}^a \tag{41}$$

$$\tilde{N} = \bar{N} - \Xi[(1-\tilde{\tau})A\tilde{z}^a - \tilde{b}\tilde{\tau}A\tilde{z}^{a+1}] \tag{42}$$

Equations (33)-(42) describe a system of 10 equations with 10 unknowns, $\tilde{z}$, $\tilde{b}$, $\tilde{\tau}$, $\tilde{\omega}$, $\tilde{N}$, $\tilde{\rho}$, $\tilde{\kappa}_g$, $\tilde{\lambda}_N$, $\tilde{\kappa}$, $\tilde{c}$. Due to the complexity of the system, we resort to numerical simulations. We aim first, to examine the role of Ramsey government in equilibrium selection, and second, to examine the effect of an increase in technological progress (increase in A) on the patience level, policy instruments, growth and the environment. We follow exactly the same numerical parameter values used in the DCE, except for the endogenous policy instruments, $\tilde{\tau}$ and $\tilde{b}$, that are derived through the Ramsey objective.

Out of the good and bad equilibria (that existed under the DCE), the bad equilibrium is eliminated under optimal fiscal policy to yield a unique equilibrium with high growth and environmental quality.[19] This happens because the government chooses the aggregate endowments

[19] Note that for $A = 1$ and the endogenous taxes from the Ramsey problem, the DCE solution gives two equilibria. Thus, the Ramsey problem provides additional restrictions that lead to a unique equilibrium.

(that are taken as given in the DCE) to choose a consumption and saving path that puts the economy in the high growth equilibrium, and then uses the policy instruments to attain the welfare-maximizing objective.

Table 2. Technological Progress, Ramsey Fiscal Policy and the Environment

A	$\tilde{z}$	$\tilde{b}$	$\tilde{\tau}$	$\tilde{\omega}$	$\tilde{N}$	$\tilde{\rho}$	$\tilde{g}$
1	0.6172	0.6773	0.4475	0.4651	0.1258	0.1135	0.2132
1.01	0.6122	0.6782	0.4495	0.4696	0.1257	0.1143	0.2160
1.02	0.6074	0.6790	0.4515	0.4741	0.1256	0.1152	0.2187
1.03	0.6026	0.6799	0.4534	0.4786	0.1256	0.1160	0.2215
1.04	0.5980	0.6808	0.4553	0.4831	0.1255	0.1169	0.2243
1.05	0.5933	0.6816	0.4573	0.4876	0.1254	0.1177	0.2271

Regarding changes in technology, our numerical results in Table 2 show that higher TFP raises output and creates incentives for the utilitarian government to generate higher tax revenues and allocate a higher proportion of its spending towards infrastructure. This results in even higher growth, even if this comes at the cost of slightly lower environmental quality. This outcome is in contrast to the dynamics of the DCE scenario where policy instruments are exogenous. Intuitively, after an increase in TFP, government expenditures on infrastructure become more effective in raising output. In turn, the government has an incentive to increase the allocation of revenues towards infrastructure so as to increase growth, and then to generate a higher tax base to finance expenditures for the environment. However, the consumption effect of higher growth outweighs that of higher abatement expenditures and causes a net increase in pollution. Interestingly, in our numerical simulations, even though we used a higher weight on environmental preferences vis-a-vis consumption, $(1-v=0.8)$, the net utility benefit of raising consumption is positive.

Result 2 *The Ramsey government leads the economy to a unique equilibrium that corresponds to the high-growth DCE regime. Under an increase in technology, government reallocation of public revenues from environment to infrastructure has a positive effect on growth while negatively affecting environmental quality.*

5 Conclusion

The objective of this paper was to explore possible explanations about two stylized facts: (i) across countries, advanced economies on average perform better in terms of growth and environmental quality, while developing countries often stagnate with low growth and low environmental quality; (ii) fast-growing economies could actually end up polluting the environment, ex post, despite there being increases in TFP, which could have been utilised to finance pollution abatement. We have studied an endogenous growth model of the environment, both for a decentralized economy and for an economy with an optimizing (Ramsey) government. In our set-up, the representative agent derived utility from private consumption and environmental quality, and an important feature of the utility function was that the rate of time preference was a decreasing function of the quality of the environment. Also, the environment was degraded by pollution, which was a by-product of consumption, and was replenished by abatement activities undertaken by the government. Other than the environment, the government also spent on infrastructure from the income taxes it generated, while balancing its budget. Externalities in production were generated by public capital, and the services from infrastructure positively affected the efficiency of abatement.

Our results for a decentralized economy highlight the existence of multiple equilibria. Here, the good equilibrium is characterized by a higher growth rate driven by a higher private-to-public capital ratio, higher marginal productivity of capital, lower propensity to consume resulting in lower pollution, and higher environmental quality. This, in turn, implies a lower degree of impatience, thus strengthening the growth channel and leading to ever-increasing growth and better environmental quality at the same time. The bad equilibrium is characterized by exactly the opposite effects, pushing the economy in a downward spiral. Technological progress in such an economy has adverse effects on growth and the environment, in sharp contrast to the favourable effects of the same for the good equilibrium.

For the case of a Ramsey-government that chooses its policy instruments to maximize agents' welfare, our results demonstrate that the bad equilibrium is eliminated, and the unique equilibrium that remains is a high-growth equilibrium. The response to higher TFP in this case is for the government to spend a higher proportion of its revenue on infrastructure, which would dynamically lead to a higher growth rate and utility levels in the long-run, even if these come at the cost of a somewhat lower environmental quality, ex post. We hope that our findings will provide valuable insights into the complex relationships that exist among governmental policy, economic growth and the environment.

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Appendix A: Data in support of Facts 1 and 2

Considering China in relation to some of its neighbouring countries in geographic terms, we can observe two trends: first, that the EPI and GDP per capita of China are both higher (sometimes, considerably more so) than countries like Nepal, Pakistan, Tajikistan, India and Bangladesh; and second, that while China's EPI is very similar to some other neighbouring countries (like Bhutan, Kyrgyz Republic and Laos), its GDP per capita is much higher than those countries. This information is reported in Tables A1 and A2 below, respectively. Table A1 shows that in relation to China, the other countries perform relatively poorly in terms of the environment index as well as the income per capita measure (in particular, Tajikistan and Bangladesh fare rather badly in terms of environment and income performance), which is in conformity with Fact 1, suggesting the presence of multiple equilibria. On the other hand, Table A2 shows that China has almost double the income per head of Bhutan, but has a lower EPI value; comparing China with Laos and Kyrgyz Republic, we find that China has about three times more income per head than those two countries but only slightly better environmental quality, which suggests Fact 2, that economic policies in fast-growing countries may not be environmentally friendly relative to some slower-growing nations.

Table A1: Data to substantiate Fact 1

COUNTRIES	EPI	GDP per capita
China	43	13216.50
Nepal	37	2370.05
Pakistan	34.58	4844.22
Tajikistan	31.34	2690.75
India	31.23	5707.65
Bangladesh	25.61	3124.37

Table A2: Data to substantiate Fact 2

COUNTRIES	EPI	GDP per capita
China	43	13216.5
Bhutan	46.86	7867.2
Kyrgyz Republic	40.63	3322.2
Laos	40.37	5320.4

Appendix B: Proof of Proposition 1

Let us first investigate the conditions for a well-defined equilibrium in the long run. In order for $\hat{\omega}(\hat{z}) > 0$ to hold, we must have $\hat{z} < \frac{1-\tau}{b\tau}$ from (23). Combining all the above we get the following for the domain of $\hat{z}$: $\left(\frac{\delta}{b\tau}\right)^{\frac{1}{a}} < \hat{z} < \frac{1-\tau}{b\tau}$.

The method will be to separate function $\Phi(\hat{z}) \equiv -Ab\tau\hat{z}^a + Aa(1-\tau)\hat{z}^{a-1} - \rho(\bar{N} - \Xi[(1-\tau)A\hat{z}^a - b\tau A\hat{z}^{a+1}])$ in two functions and find their intersection to solve it. We define $\Gamma(\hat{z}) \equiv Aa(1-\tau)\hat{z}^{a-1} - Ab\tau\hat{z}^a$ and $\Lambda(\hat{z}) \equiv \rho(\bar{N} - \Xi[(1-\tau)A\hat{z}^a - b\tau A\hat{z}^{a+1}])$. Both $\Gamma(\hat{z})$ and $\Lambda(\hat{z})$ are continuous in $\hat{z}$. In order for $\hat{\omega}(\hat{z}) > 0$ to hold we must have $\hat{z} < \frac{1-\tau}{v\tau}$.

Equation $\Gamma(\hat{z})$ has the following properties:

1. $\lim_{\hat{z}\to 0}\Gamma(\hat{z}) = +\infty$, $\lim_{\hat{z}\to\frac{1-\tau}{b\tau}}\Gamma(\hat{z}) = Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^a$.
2. $\frac{\partial\Gamma(\hat{z})}{\partial\hat{z}} < 0$, $\frac{\partial^2\Gamma(\hat{z})}{\partial\hat{z}^2} > 0$.

From the properties of $\Gamma(\hat{z})$ is follows that it is a strictly decreasing and convex function in its domain, starts from $+\infty$ and ends at $Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^a$.

Equation $\Lambda(\hat{z})$ has the following properties:

1. $\lim_{\hat{z}\to 0}\Lambda(\hat{z}) = \rho(\bar{N}) = \check{\rho}$, $\lim_{\hat{z}\to\frac{1-\tau}{b\tau}}\Lambda(\hat{z}) = \rho(0) = \check{\rho}$.
2. $\frac{\partial\Lambda(\hat{z})}{\partial\hat{z}} = -\rho'(.)\left[aA(1-\tau)\hat{z}^{a-1} - b\tau(1+a)\hat{z}^a\right]$. We have $\frac{\partial\Lambda(\hat{z})}{\partial\hat{z}} > 0$ for $a(1-\tau)\hat{z}^{a-1} - b(1+a)\tau\hat{z}^a > 0 \implies \hat{z} < \frac{a(1-\tau)}{b(1+a)\tau}$ and $\frac{\partial\Lambda(\hat{z})}{\partial\hat{z}} < 0$ for $\hat{z} > \frac{a(1-\tau)}{b(1+a)\tau}$. Thus, $\Lambda(\hat{z})$ has a maximum at $\hat{z} = \frac{a(1-\tau)}{b(1+a)\tau}$.

From the properties of $\Lambda(\hat{z})$ it follows that it is an inverse U-shaped curve starting from $\check{\rho}$ and ending at $\check{\rho}$.

Assuming equilibrium existence, from the properties of $\Lambda(\hat{z})$ and $\Gamma(\hat{z})$ it follows that there exist one or two positive balanced growth rates. For low values of $\hat{z}$, since $+\infty > \check{\rho}$ we get that $\Gamma(\hat{z})$ lies above $\Lambda(\hat{z})$. Also, for the upper bound value of $\hat{z}$, $\Gamma(\hat{z}) = Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^a$ and $\Lambda(\hat{z}) = \check{\rho}$. Since both functions are continuous, if $Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^a < \check{\rho}$, which means that $\Gamma(\hat{z})$ starts above and ends below $\Lambda(\hat{z})$ implying that $\Gamma(\hat{z})$ will cross $\Lambda(\hat{z})$ once and there will exist a unique balanced growth rate. Thus, $Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^a < \check{\rho}$ is a sufficient parametric condition for a unique balanced growth rate.

If $Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^{a} \geq \check{\rho}$ then there can exist two balanced growth rates because $\Lambda(\hat{z})$ is an inverse U-shaped curve, while $\Gamma(\hat{z})$ strictly monotone and decreasing, so $\Gamma(\hat{z})$ can cross $\Lambda(\hat{z})$ at most two times. Thus, $Aa(1-\tau)(\frac{1-\tau}{b\tau})^{a-1} - Ab\tau(\frac{1-\tau}{b\tau})^{a} \geq \check{\rho}$ is a necessary parametric condition for multiplicity.

Ranking of Equilibria: In the case of multiple balanced growth rates $\Lambda(\hat{z})$ and $\Gamma(\hat{z})$ intersect twice, for $\hat{z}_1$ and $\hat{z}_2$. Let those two balanced growth rates ranked as $\hat{z}_1 > \hat{z}_2$. To find the corresponding ranking of $\hat{\omega}_1$ and $\hat{\omega}_2$ we solve $\hat{\omega}$ in the steady-state, and we take the derivative with respect to $\hat{z}$, $\frac{\partial \hat{\omega}}{\partial \hat{z}} = (a-1)(1-\tau)A\hat{z}^{a-2} - abA\tau\hat{z}^{a-1} < 0$. Thus, $\hat{\omega}$ is a strictly decreasing function of $\hat{z}$, so $\hat{z}_1 > \hat{z}_2 \Longrightarrow \hat{\omega}_1 < \hat{\omega}_2$. To find the ranking of g_1 and g_2 we take the derivative of g with respect to $\hat{z}$, $\frac{\partial g}{\partial \hat{z}} = b\tau a\hat{z}^{a-1} > 0$. Thus, g is an increasing function of $\hat{z}$, so $\hat{z}_1 > \hat{z}_2 \Longrightarrow g_1 > g_2$. The ranking for the rate of time preference, $\rho(\hat{z} \cdot \hat{\omega}(\hat{z})) = \Lambda(\hat{z})$, which is a non-monotonic function of $\hat{z}$, comes from the analysis above. As $\Gamma(\hat{z})$ lies above $\Lambda(\hat{z})$ and is monotonically decreasing, it cannot cross twice $\Lambda(\hat{z})$ in its increasing part. Then, $\hat{z}_1 > \hat{z}_2 \Longrightarrow \Lambda(\hat{z}_1) < \Lambda(\hat{z}_2) \Longrightarrow \Lambda(\hat{z}_1) < \Lambda(\hat{z}_2) \Longrightarrow \rho_1 < \rho_2$. So, in case of two balanced growth rates with high growth, g_1, and low growth, g_2, the endogenous variables are ranked as $\rho_1 < \rho_2$, $\hat{\omega}_1 < \hat{\omega}_2$, $\hat{z}_1 > \hat{z}_2$.

Appendix C: Numerical analysis

Table A3. Values for parameters and exogenous policy instruments

Parameters	Description	Value
α	share of private capital in the production function	0.5
A	total factor productivity	$1 - 1.05$
δ	capital depreciation rate	0.025
δ_N	persistence level of natural resources	0.9
ξ	effect of infrastructure on the efficiency of abatement	1
s	polluting effect of economic activity	1
$\bar{N}$	environmental quality without degradation	20
γ	slope of the impatience function	15
$\breve{\rho}$	upper bound for the impatience function	2
τ	income tax rate	0.447
b	share of infrastructure spending in total spending	0.677