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Public investment in environmental infrastructures, growth, and the environment

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Public investment in environmental infrastructure, growth, and the environment

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Abstract

This paper studies the relationship between infrastructure, growth and the environment. By distinguishing between polluting and environmental infrastructure we analyze whether investing in the latter can be good both for growth and the environment. We also scrutinize the potential conflicts between 'growth maximizing' and 'welfare maximizing' policies. Our main conclusion is the following. For an economy that has already invested a lot in productive, but polluting, infrastructure, increasing the share of public resources devoted to environmental infrastructure is a means not only to promote growth but also to enhance welfare. For such an economy, any efficient economic stimulus plan should give priority to the provision of greener public infrastructure.

Keywords: productive infrastructure, environmental infrastructure, environmental quality, growth

JEL Classification: Q56, D62, D91

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1 Introduction

As a response to the 2008 financial crisis, many governments launched huge stimulus plans with an unprecedented emphasis on ‘green spending. According to Strand and Toman (2010), out of an identified overall proposed stimulus spending of US\$2.8 trillion after the 2008 crisis, about US\$435 billion (about 15 percent) can been classified as “green”. More important to our purpose, much of the proposed green spending (more than two-thirds of the total; and for China almost 100 percent) is for infrastructure.[1] The rationale behind such stimulus plans is the idea of “green growth”, and in particular the idea that public spending on “green” public infrastructure could both promote economic growth and improve environmental quality. See OECD (2009), the World Bank (Shalizi and Lecocq, 2009) or Barbier (2009).

The empirical evaluation of the impact of public investment programs on economic growth and private output was originally addressed by Arrow and Kurtz (1970), and was reignited 20 years later by Aschauer's empirical paper (1989a,b). Aschauer (1989a,b) suggests that public capital was a powerful engine for growth in the United States. His results suggest that public capital paid for itself three times over in the form of additional tax revenues. In the event, Aschauer's works were criticized on econometric grounds and many subsequent studies failed to confirm the likelihood of such significant effects. The surveys by Hulten and Schwab (1993) or Gramlich (1994) suggest a more balanced view: public capital does support growth, but probably less strongly than initially suggested by Aschauer. By and large, as noted by Ottaviano (2008), the general assessment that public infrastructure has a positive impact on private output and employment seems to have survived the application of more recent and sophisticated econometric techniques, *e.g.* Gramlich (1994), Peirera and Flores (1999) or Röller and Waverman (2001).

Barro (1990) was the first to model the relationship between public infrastructure and growth on a theoretical basis. Infrastructure is introduced as an externality in the production function. Public spending is financed by an income tax. Such a policy typically involves two opposite effects. First, the provision of infrastructure stimulates growth through its positive impact on production. Second, public investment crowds out private investment in physical capital. It is then possible to discover the distribution of economic resources between private and public capital that maximizes growth. Since the seminal contribution of Barro, literature on the topic has grown exponentially. Glomm and Ravikumar (1994) and Fisher and Turnovsky (1998) investigate the impact of congestion associated with the use of infrastructure. Eicher and Turnovsky (1999) model the process of infrastructure provision as a true (public) production sector using labor and physical capital. Turnovsky and Pintea (2006) assess the role of public infrastructure on economic performance in a small open economy. Devereux and Mansoorian (1992) consider a two-country framework and examine the effect of strategic interaction between countries on infrastructure provision and growth. De la Croix and Delavallade (2009) analyze how the composition of public investment can be distorted when there is corruption. Surprisingly, despite this expanding literature, an analysis of the relationship between infrastructure, growth and the environment is still lacking. The exception is Greiner (2005), who introduces polluting emissions as a production by-product in a model where the public policy task is twofold. The government levies a tax on polluting firms in addition to the income tax. Public revenue is then divided between an abatement activity and the provision of infrastructure. Greiner sheds light on the effect of fiscal policy on growth and also characterizes the optimal policy.

The present paper puts the emphasis on the relationship between infrastructure, growth and the environment by paying particular attention to the distinction between polluting and envi-

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[1] OECD (2009) contains a similar table but with different classifications of items.

ronmentally friendly infrastructure. Our aim is to address the following important question: can an economic stimulus plan consisting of investment in environmentally friendly infrastructure succeed in promoting growth and improving welfare? To answer this question, we develop a growth model with public infrastructure along the same lines as Glomm and Ravikumar (1994) and add the environmental dimension. A breakdown of public investment between two different kinds of infrastructure is made (based on the analysis of Pereira (1999), see section 2.2). Both types of infrastructure have a positive impact on production. However, they differ with respect to their effect on the environment. Some types of infrastructure are polluting (*e.g.* transportation networks) and increase pressure on the environment. Other types of infrastructure are specifically aimed at improving environmental quality (such as waste management systems).

In our model, because environmental quality enters into the household's utility function, there exists an indirect relationship between infrastructure and household utility. How environmental infrastructure contributes to households quality of life has received very little attention in the literature. From an empirical standpoint this may be due to the fact that such benefits are un-priced, as they are outside the market, and thus rather difficult to evaluate.[2] However, the quality-of-life benefits related to public investment should be considered in the debate, as well as their effect on economic growth and consumption. For many uses, households are direct users of public infrastructure. And much of this infrastructure is specifically designed for them and is related to environmental quality: water supply, energy facilities, public buildings and infrastructure, natural recreation facilities, and so forth. This dual effect of public infrastructure on households utility, through private consumption and environmental quality, will be considered in our model. It is a key issue if one wants to tackle the issue of environmental quality in relation to economic growth.

The analysis first focuses on the competitive equilibrium, defined in terms of public policy. Compared to the existing literature, the novelty of this analysis lies in the fact that public policy encompasses two distinct instruments. The government has not only to choose the level of resources devoted to the provision of infrastructure as a whole but also to determine the share of public spending allocated to the two kinds of infrastructure. Second, the conditions for balanced and sustainable growth are identified. Finally, the growth-maximizing policy and the optimal policy - that is, the policy designed to maximize welfare - are defined and compared. The main message of this paper is that for an economy that has already invested substantially in productive but polluting infrastructure, stimulating economic growth requires a policy change toward an increase in the production of the environmentally friendly type of infrastructure. Such a switch puts the economy in a win-win situation, since producing more environmentally friendly infrastructure raises environmental quality. It turns out, however, that a policy intended to maximize the growth rate of both consumption and the environment (the two arguments of preferences) is not usually optimal from a welfare-maximization perspective. Therefore, the question of whether a policy that enhances growth is synonymous with higher welfare remains a matter for investigation. In situations where priority has been given to polluting infrastructure, we show that increasing the share of public resources devoted to environmentally friendly infrastructure is also welfare-improving.

The paper is organized as follows. Section 2 gives a precise definition of environmentally friendly infrastructure and surveys the empirical literature that analyzes the importance of

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[2] Many methods exist in environmental economics to evaluate non-market benefits of private or public investments, and they could be used in these ex post evaluations. One example is the evaluation of the benefits of urban air quality improvements by contingent evaluation or hedonic price methods. Presenting these methods is beyond the scope of this paper.

public investments in the two kinds of infrastructure, and their respective contributions to growth. Section 3 presents the model. Section 4 establishes the conditions for the existence of a balanced growth path and sustainable growth. Two policy scenarios are then considered and compared. Section 5 analyzes the effects of public support for environmentally friendly infrastructure that aims at maximizing economic growth while Section 6 focuses on policy aiming at maximizing welfare. The effects of the two policies are compared in terms of economic growth, environmental quality and welfare. Our main conclusions are summarized in the last section.

2 The literature on infrastructure and growth

2.1 Defining environmental infrastructures

A general definition of public infrastructure is provided by the U.S. National Research Council, which adopts the term "public works infrastructure" to include "both specific functional modes - highways, streets, roads, and bridges; mass transit; airports and airways; water supply and water resources; wastewater management; solid-waste treatment and disposal; electric power generation and transmission; telecommunications; and hazardous waste management - and the combined system these modal elements comprise. A comprehension of infrastructure spans not only these public works facilities, but also the operating procedures, management practices, and development policies that interact together with societal demand and the physical world to facilitate the transport of people and goods, provision of water for drinking and a variety of other uses, safe disposal of societies waste products, provision of energy where it is needed, and transmission of information within and between communities."[3]

Public infrastructure thus appears to play a key role in the management of environmental quality. This role is stressed, among many other institutions, by the US Environmental Agency[4] and the European Commission under the ERDF programs.[5]

In the same vein the OECD points out that large public investment needs to be made in transition economies, such as the new EU Member States, to clean up the environment and attain a satisfactory quality of life. As an example, the amount of required investment in infrastructure for Poland was evaluated at between 25 to 51 billion 1998 euros (OECD, 2001, p. 133).

How can one define green infrastructure? In the EU Funding for the Environment Handbook' for the 2007 - 13 ERDF programming period, the WWF identifies the following needs for the environment in terms of infrastructure (WWF, 2005):

- Infrastructure maintenance: running costs incurred to meet depreciation of infrastructure
- New infrastructure specific to the maintenance or restoration of habitats and species: includes an array of measures for the creation of infrastructure specific to the management of the environment, e.g. for water management in peat bogs and marshes

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[3] National Research Council (1987), page 4, quoted by Ottaviano (2002), page 18.

[4] In 2002, the U.S. EPA released the 'Clean Water and Drinking Water Gap Analysis Report'. This report estimated that if investment in water and wastewater infrastructure does not increase to address anticipated needs, the funding gap over the next 20 years could grow to \$122 billion for Clean Water capital costs and \$102 billion for Drinking Water capital costs. See: *www.epa.gov/waterinfrastructure/infrastructuregap.*

[5] The ERDF (European Regional Development Fund) aims at reducing regional disparities in the EU and at supporting structural development and adjustment of regional economies and promoting environmentally sound growth. The scope of assistance is productive investments, infrastructures, other development initiatives (services to enterprises, financing instruments) and environmental protection. See: *ec.europa.eu/regional_policy.*

- Public use infrastructure: infrastructure for public use that is conducive to environmental protection and management (e.g. infrastructure increasing the amenity value of sites, such as signage, trails, observation platforms and visitor centers)
- Fire prevention, control and management: includes the preparation of warden and fire-control plans, the development of relevant infrastructure and the acquisition of equipment
- Infrastructure affecting Natura 2000:[6] includes post-construction management measures, provision of corridors and passages for species and demolition activities where warranted

Each type of infrastructure may have a specific impact on the environment. In what follows we will make clear which ones we consider in our analysis.

2.2 Public investment in infrastructure, growth and the environment: empirical investigations

We mentioned in the introduction the general literature devoted to the empirical evaluation of public investment in infrastructure on economic growth. Some recent papers focused on key features that will be of importance for our purpose, in particular by disaggregating types of infrastructure and explicitly considering environmental ones. Of particular interest for us are the papers of Peirera and Flores (1999), and Peirera (1999). These authors make use of US annual data for the period 1956-1997. They consider five kinds of non-military public investments and analyze the share of each kind in total public investments as well as the link to the private sector.[7] Their main conclusions can be summarized as follows:[8]

1. Infrastructure investments in highways and roads affect private productivity through the provision of transportation services for both final and intermediary goods; they represented 28.4% of total investment over the sample period,
2. Infrastructure investments in electrical and gas facilities and in transit systems, which guarantee secure and affordable access to energy facilities for the private sector; they accounted for 12% of total investments over the period,
3. Educational buildings, general office buildings, police and fire stations, courthouses, passenger terminals, and so forth: such investments ensure promotion of knowledge and well-being of the labour force as well as the setting of rules and regulations that increase private sector productivity; they have shown a stable pattern of around 32% of total public investment, except notably during the 1980s, when the proportion fell to 17%,
4. Infrastructure investments in sewage and water supply systems which as with energy access, directly enter private sector production processes; accounted for 16% of public investment; it peaked at 27.7% in 1978-87,

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[6] "Natura 2000 is the centrepiece of EU nature & biodiversity policy. It is an EU wide network of nature protection areas established under the 1992 Habitats Directive. The aim of the network is to assure the long-term survival of Europe's most valuable and threatened species and habitats" (European Commission, 2002). See: *http://ec.europa.eu/environment/nature*.

[7] In an extension of this work, Pereira (2001) analyzed crossed-elasticities between these five kinds of public investment and five kinds of private investments.

[8] As these figures are means over slightly different time slices, they do not exactly sum up to 100.

5. Investments in conservation and development structures (intended for water, land, and animal protection), and civilian equipment, which together represented 14.3% of total investment and play a supportive role in the preservation of private capital stock; their share increased in the last years of the sample period and reached 23% of total investment.

The third category can unambiguously be identified as environmental infrastructure. The fourth also, but its productive interaction with private capital seems to be less straightforward. Both categories experienced rather sharp variations over the sample. Together they represented 30.3% of total public expenditures in infrastructure on the average over the period 1956-1997.

Peirera (1999) implemented an econometric analysis to quantify the impact of these investments on private output growth. Its main results are the following. First, in the long term, public investment globally crowds in private investment. He also finds that aggregate public investment has a positive effect on private output, thus being an engine for long-term growth. Second, all five types of public investment crowd-in private investment, but with specific magnitudes. Infrastructure investments in electricity and gas facilities, in transit systems, and those in sewage and water supply systems display the highest rates of return (16.1% and 9.7%, respectively), closely followed by investments in educational, hospital, and other public buildings (8.9%). Investments in conservation and development structures also contribute positively to growth with a rate of return of 7.2%.[9]

Another paper is the one by Moomaw *et al.* (1995). These authors found that States generally achieve greater returns from investing in water and sewerage systems than from investing in highways. Moomaw *et al.* (1995) also introduce the idea that the effectiveness of an investment depends on the way it is used when available. By extending their intuition it seems clear that some infrastructure investments may well be under-used, or ill-used, which would certainly reduce their effectiveness. This suggests that both investment costs and operating costs (including maintenance costs) play a key role in the effectiveness of public investment in infrastructure. Finally, they also discuss and evaluate the idea that the economic impact of public investments is influenced by the characteristics of the region considered. This links into the issue of the stage of development of the economy considered, notably in terms of pre-existing infrastructure level, and this is a point that will be discussed further with the model we shall develop.

3 The model

The present framework is built on Glomm and Ravikumar (1994)'s growth model with infinitely-lived agents and combines considerations for growth, the provision of infrastructure and the environment. In a perfectly competitive world, the firms produce a single homogeneous good used both for consumption and investment. A distinction is made between two types of infrastructure: polluting *vs.* environmental. Both public capital contribute to production but differ with respect to their environmental impact. Actually, one creates an environmental pressure while the other allows the economy to keep this pressure under control.

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[9] The annual rates of return are calculated by using the marginal productivities and assuming a life horizon of twenty years for all types of public capital assets. That is, the rate of return applied to one dollar over a twenty-year period yields the value of the accumulated marginal product.

3.1 Private agents

3.1.1 Firms

The representative firm produces a homogenous good (Y_t), which can be consumed (c_t) or invested (I_t). The production technology uses two private inputs, capital (K_t) and labour (L_t). Infrastructure enhances the productivity of the private factors, and for this reason it can be considered as a production factor. Therefore, polluting infrastructure (G_{pt}) and environmental infrastructure (G_{et}) have a positive but different impact on production. Formally, the techology is defined as a Cobb-Douglas function with constant returns to private inputs:

$$Y_t = AG_{pt}^{\sigma} G_{et}^{\theta} K_t^{\alpha} L_t^{1-\alpha} \ \alpha \in (0,1), \ \sigma, \theta > 0 \tag{1}$$

The competitive firm maximises profits taking as given the factor prices. For the sake of simplicity we assume that capital fully depreciates in one period. This yields the usual equality between factor prices and marginal productivities:

$$w_t = (1-\alpha) AG_{pt}^{\sigma} G_{et}^{\theta} K_t^{\alpha} L_t^{-\alpha} \ , \tag{2}$$

$$r_t = \alpha AG_{pt}^{\sigma} G_{et}^{\theta} K_t^{\alpha-1} L_t^{1-\alpha} \ . \tag{3}$$

with w_t the wage rate and r_t the interest rate.

3.1.2 Households and the environment

Consumption and investment decisions are undertaken by a representative infinitely-lived household. The household derives utility from consumption and an index of environmental quality Q_t. Preferences are given by:

$$U_t = \ln c_t + \eta \ln Q_t, \tag{4}$$

where $\eta > 0$ describes the environmental concern.

The agent supplies inelastically one unit of labor, and earns the returns on investment. Her total income (net of taxes) is used for the purchase of the commodity and for the investment in capital, over the life-cycle:

$$K_{t+1} = (1-\tau_t)(w_t + r_t K_t) - c_t, \tag{5}$$

and it is worth noting that the budget constraint depends on the government taxation policy $\{\tau_t\}$, which the agent takes as given.

The environmental quality Q_t is an index defined as the inverse of the environmental pressure P_t:

$$Q_t = \frac{1}{P_t} \text{ with } P_t = K_t^{\phi} G_{pt}^{\delta} G_{et}^{-\rho}, \tag{6}$$

where ϕ, $\delta > 0$ represent the respective impact of capital and polluting infrastructures on the environment, and $\rho > 0$ is the parameter that indicates the efficiency of green infrastructures in depollution. [10] When $\delta = \rho$, the marginal impacts of the two kinds of infrastructures on the environment exactly offset each other. Having $\rho > \delta$ means that, if one invests the same

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[10] In this paper we distinguish between polluting and depolluting infrastructure. Nevertheless, it must be stressed that the whole analysis still holds when considering two polluting infrastructures, one being more polluting than the other. The key for interpreting the results will be the relative pollution intensity and the relative contribution to production of the two types of infrastructures. For example, our framework is suitable for a discussion about investments in highways *versus* railways.

amount of money in both kinds of infrastructures, the positive impact of the environmental infrastructures on environment quality will be stronger than the negative impact caused by the polluting infrastructures. The contrary holds if $\rho < \delta$. When considering also the impact of capital on the environment, *i.e.* the whole polluting function (6), then, having $\rho > \phi + \delta$ means that environmental infrastructures are efficient enough to compensate for the damages due to both physical capital and polluting infrastructures. The opposite prevails when $\rho < \phi + \delta$. The special case where $\rho = \phi + \delta$ represents the case where environmental infrastructures exactly offset the impacts of K and G_p on the environment. Because these parameters capture the productive and environmental charateristics of infrastructures, they will naturally appear when discussing our results.

The variable P_t is a broadly defined index that is built on the aggregation of many types of environmental pressures, such as the composite index developed by the Yale Center for Environmental Law and Policy and the Columbia University.[11] The environmental pressure is mainly related to the use of physical capital. But, in addition, the first category of infrastructures also contribute to the environmental burden. For example, the use of transportation networks or public buildings generates pressures on the environment such as waste generation, noise or polluting effluents. Conversely, the second category of infrastructures are intended to control or reduce the pressure exerted by human activities on the environment. Examples of environmental infrastructures are given by waste management systems, sewage and water supply systems, etc. (see Section 2).

The household has no direct influence on the quality of the environment and takes Q_t as given. She allocates her income between consumption and investment to maximize the sum of her discounted utility, with $\beta \in (0, 1)$ the discount factor:

$$\max_{\{c_t, I_t\}} \sum_{t=0}^{+\infty} \beta^t \left(\ln c_t + \eta \ln Q_t\right) \tag{7}$$

given $K_0, G_0, \{w_t, r_t, \tau_t\}_{t=0}^{\infty}$, subject to $c_t, K_{t+1} \geq 0$, $\forall t$, and the budget constraint (5). In sum, the household faces the usual issue of how to allocate optimally her consumption possibilities over time, *i.e.* the optimal choice between current consumption and investment.

3.2 Public policy in infrastructures

The government is responsible for the financing and provision of public infrastructures. In that purpose it levies a tax $\tau_t \in (0, 1)$ on the representative agent's income. Public spending at period t determines the overall level of infrastructures available the next period according to the following budget constraint:[12]

$$G_{t+1} = \tau_t (w_t L_t + r_t K_t). \tag{8}$$

Under the assumption of private constant returns to scale, once profits are maximized, the resulting quantity of the public capital can be expressed as a share of the national product,

$$G_{t+1} = \tau_t A G_{pt}^{\sigma} G_{et}^{\theta} K_t^{\alpha} L_t^{1-\alpha}. \tag{9}$$

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[11] For further information, see: *epi.yale.edu/home*.

[12] Again, in accordance with Glomm and Ravikumar (1994), we assume that infrastructures fully depreciate in one period. Both restrictions on the depreciation rate of capital and infrastructures can be relaxed. They are used to simplify the analysis in particular because they provide closed form solutions. In any case, assuming partial depreciation would not change our results.

The novelty in our model, as in de la Croix and Delavallade (2009), is that the public policy is two-dimensional. Firstly, by choosing the tax rate on income, the government determines the overall provision of public infrastructures in each period. This is the dimension addressed in the models on growth and infrastructures. Secondly, because of the distinction between polluting and environmental infrastructures, the new and important issue in our model is that the government can choose how to share public expenditures among the two types of infrastructures. Indeed, the government has not only the choice of 'how much' public infrastructures to provide, but also the issue of 'which kind' of infrastructures to provide to the economy.

So, the total amount of public capital at period t is split between polluting and environmental infrastructures:

$$G_t = G_{pt} + G_{et},$$

and $\varepsilon_t \in (0,1)$ will stand for the share of polluting infrastructures in the total. This ε_t constitutes the new policy instrument available for the policy maker, besides the tax rate τ_t.

The following section studies the competitive equilibrium and defines the conditions for a sustainable growth path in the economy.

4 The competitive equilibrium

Given an arbitrary public policy $\pi = \{\tau_t, \varepsilon_t\}_{t=0}^{\infty}$, with $\tau_t, \varepsilon_t \in (0,1)$, a competitive equilibrium makes consistent all the decisions undertaken by the private agents (households and firms).

Definition 1 *Given the public policy π, a competitive equilibrium π-CE is a sequence of aggregate variables $\{c_t, K_t, L_t, G_t, Q_t\}_{t=0}^{\infty}$ and prices $\{w_t, r_t\}_{t=0}^{\infty}$ such that:*

(i) agents are at their optimum,

(ii) all markets clear: $L_t = 1$, $K_{t+1} = I_t$,

(iii) the dynamics of infrastructures are given by (9),

(iv) environmental quality is defined according to (6).

4.1 Artificial problem

In accordance with Glomm and Ravikumar (1994), it is possible to formulate an artificial problem whose resolution yields the consumption and investment decisions:

$$\begin{array}{l} \max\limits_{\{c_t, K_{t+1}\}} \sum_{t=0}^{+\infty} \beta^t \left(\ln c_t + \eta \ln Q_t\right) \\ s.t. \left\{ \begin{array}{l} K_{t+1} = (1-\tau_t) A G_{pt}^{\sigma} G_{et}^{\theta} K_t^{\alpha} - c_t \\ K_0, \{\tau_t, G_{pt}, G_{et}\}_{t=0}^{\infty} \text{ given.} \end{array} \right. \end{array} \tag{10}$$

The solutions for this problem are provided by the following proposition.

Proposition 1 *The decision rules:*

$$c_t = (1-\beta\alpha)(1-\tau_t) A G_{pt}^{\sigma} G_{et}^{\theta} K_t^{\alpha} \tag{11}$$

$$K_{t+1} = \beta\alpha(1-\tau_t) A G_{pt}^{\sigma} G_{et}^{\theta} K_t^{\alpha} \tag{12}$$

form the unique solution to the artificial problem (10). These solutions coincide with the competitive equilibrium π-CE.

Proof. Follows the same logic as Glomm et Ravikumar (1994), see appendix A for details. ■

In other words, the pair (11, 12), together with (9), are the solutions to the intertemporal problem of how to share economic resources between consumption and investment over the life-cycle.

4.2 Balanced and sustainable growth paths

Taking into account the sharing of public expenditures between the two types of infrastructures, equilibrium dynamics are written as a dynamical system in $\{K_t, G_t\}$:

$$\begin{cases} K_{t+1} = \beta\alpha(1-\tau_t)A\varepsilon_t^{\sigma}(1-\varepsilon_t)^{\theta}G_t^{\sigma+\theta}K_t^{\alpha} \\ G_{t+1} = \tau_t A\varepsilon_t^{\sigma}(1-\varepsilon_t)^{\theta}G_t^{\sigma+\theta}K_t^{\alpha} \end{cases} \tag{13}$$

and environmental quality is given by $Q_t = (\varepsilon_t)^{-\delta}(1-\varepsilon_t)^{\rho}x_t^{-\phi}G_t^{\rho-\delta-\phi}$ with x_t the ratio between capital and infrastructures.

Hereafter, we investigate whether economic growth may be sustainable. Attention is paid to situations where there are constant returns to augmentable factors, K and G that is, to situations where the economy grows along a balanced growth path.

Definition 2 *A balanced growth path (BGP) of the economy is a path where infrastructures, consumption and physical capital grow at the same constant rate. Growth is sustainable if and only if utility is non-decreasing along the BGP.*[13]

The conditions for the economy to experience a BGP and a sustainable growth are given in the following proposition.

Proposition 2 *i/ Assume $\sigma + \theta = 1 - \alpha$, then, in the long run, physical capital and infrastructures grow at a common constant rate g:*

$$g = \chi - 1 \text{ with } \chi = (\beta\alpha(1-\tau))^{\alpha}\tau^{1-\alpha}A\varepsilon^{\sigma}(1-\varepsilon)^{1-\alpha-\sigma} \tag{14}$$

χ being the growth factor,

ii/ The BGP defined by g is sustainable if and only if $1 + \eta(\rho - \delta - \phi) \geq 0$,[14]

iii/ As for environmental quality, three different regimes are possible

$$\begin{array}{lcl} \rho > \phi + \delta & & Q_t \to \infty \\ \rho = \phi + \delta & \Leftrightarrow & Q = \left(\beta\alpha\frac{(1-\tau)}{\tau}\right)^{-\phi}\varepsilon^{-(\rho-\phi)}(1-\varepsilon)^{\rho} \\ \rho < \phi + \delta & & Q_t \to 0 \end{array} \tag{15}$$

Proof. See appendix B1. ■

The first condition on parameters ($\sigma + \theta = 1 - \alpha$) means that infrastructures as a whole must contribute sufficiently to production in order for the technology to exhibit constant returns to private and public capital. It is the usual condition made in the literature that focuses on public spending in infrastructures as the engine of growth, as initiated by Barro (1990). In addition,

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[13] So, we consider a criterion of weak sustainability. A criterion of strong sustainability would further require the environment quality to be non-decreasing along the BGP.

[14] For our analysis to be at all interesting, we restrict hereafter our attention to situations where $\chi > 1$.

weak sustainability of balanced growth requires environmental infrastructures to be efficient enough and/or environmental concern to be high enough. In the case where environmental infrastructures exactly outweight the degradation caused by the use of physical capital and polluting infrastructures, environmental quality will reach a constant level given by (15) in the long run. In the two other cases, sustainable and balanced growth can be accompanied by an ever increasing or decreasing environmental quality.

Moreover, note that when the public policy is constant over time ($\tau_t = \tau$ and $\varepsilon_t = \varepsilon$, $\forall t$) there is no transitional dynamics in the economy. The economy directly settles on the constant growth path for physical capital and infrastructures since the very first period, whereas the dynamics of the environmental quality are determined by the relationship between ρ, ϕ and δ.

We are now equipped to analyze how the policy in public infrastructures shapes economic growth and the environmental quality.

5 The effects of public policy on growth and the environment

The first important question raised in our paper is to determine the effects of a change in the policy instruments, the tax rate and the sharing of expenditures, on growth and the environment. We shall investigate first the impact of those instruments on the growth rate of the economy, and then the impact on the environment. In this section we will focus on a public policy aiming at maximizing the growth rate of the economy, as it is usually discussed when economic stimulus plans are discussed. What can be the contribution of environmental infrastructures in such a policy? And what could be the effects on the environment? Are they necessarily positive?

The following proposition characterizes the instruments under a growth-maximizing policy.

Proposition 3 *i/ The growth-maximizing tax rate is* $\tau^* = (1 - \alpha)$. *Raising the tax promotes growth if and only if* $\tau < \tau^*$.

ii/ The growth-maximizing share of polluting infrastructures is $\varepsilon^* = \sigma/(1 - \alpha)$. *Increasing the share of green infrastructures enhances growth if and only if* $\varepsilon > \varepsilon^*$.

Proof. See appendix B2. ■

The level of the growth-maximizing tax rate is the one identified in the literature that considers a unique aggregate stock of infrastructures (see Barro 1990, Glomm and Ravikumar 1994, 1997). It means that only the overall contribution of public infrastructures to production matters when defining the growth-maximizing tax rate, and not the sharing between polluting and environmental infrastructures. Let us decompose the impact of a change in the tax rate on growth. First, a higher tax means that agents have less resources to devote to consumption and investment. Indeed, according to (12), the amount that is invested diminishes. A crowding out effect occurs which causes capital accumulation to slow down. At the same time, increasing the tax allows the government to provide more infrastructures, both polluting and environmental, to the economy. More public infrastructures tends to crowd in private production. If this indirect effect is strong enough to offset the crowding out effect, then a higher tax is accompanied by a higher growth rate. There exists a critical value $\tau^* = (1 - \alpha)$ that determines which effect dominates. The (increasing) production of infrastructures stimulates growth as long as the tax rate (the marginal cost of the policy) does not exceed the impact of infrastructures in production (the marginal benefit).

The novelty brought by our analysis lies in the analysis of the impact of the sharing of public expenditures between polluting and environmental infrastructures on growth. According to Proposition 3, item *ii*, there also exists a critical value for the choice of ε. Increasing the share of polluting infrastructures in the total amount of public capital promotes growth as long as that share is below the relative weight of polluting infrastructures in the total contribution of the public capital to production. In other words, it is only when the share of environmental infrastructures is relatively low ($1-\varepsilon \leq (1-\alpha-\sigma)/(1-\alpha)$) that the government can stimulate growth by providing a higher amount of that kind of public capital to the economy.

Thus, the government is endowed with two different instruments to influence economic growth. It can change the public spending and/or its sharing between the two kinds of infrastructures. If the government is reluctant to change the global fiscal burden, τ, it can still rely on the other instrument to stimulate growth, ε. If the economy is already endowed with relatively important polluting infrastructures (*i.e.* $\varepsilon > \varepsilon^*$), then enhancing growth requires to switch to the provision of the other environmental infrastructure. That holds true even if the contribution of polluting infrastructures to production is higher than the contribution of environmental infrastructures (that is, when $\sigma > 1-\alpha-\sigma$). In other words, the productivity gap can be more than offset by the imbalance between the two types of public expenditures when priority has been first given to investments in polluting infrastructures.

A rough empirical discussion can be made by using the figures provided by Pereira (1999) and already mentioned in Section 2. Considering that public spending amounts to 60% of GDP, we have that $\sigma+\theta = 0.6$. Following the literature we consider that G_g and G_p gather all the spending related to infrastructures, *i.e.* operational, maintenance costs and wages. By using Pereira's figures we have that spending in green infrastructures amounts to 30.3% of total spending, so $\sigma = 0.4182$ and $\theta = 0.1818$. Finally we take as the share of capital in the production function $\alpha = 0.4$. According to Pereira, data for the US indicate that the share of green infrastructures was 30.3% on the average for the period 1956-1997. Our model suggests that the share of green infrastructures that would have maximized economic growth and environmental quality should have been 39%. So there is room for more green public investments in the US economy.

Let us now turn to the effects of a growth-maximizing policy on the environment. We shall restrict our analysis to the more relevant case where economic growth is non negative ($\chi \geq 1$). The effects of a growth-maximizing policy on the environment can be summarized as follows:

Proposition 4 *i/ When* $\rho > \phi+\delta$ *(resp.* $\rho < \phi+\delta$*), then the growth rate of the environmental quality is maximal (resp. minimal) if and only if* $\{\tau, \varepsilon\} = \{\tau^*, \varepsilon^*\}$.

ii/ When $\rho = \phi+\delta$*, then the level of environmental quality is always increasing in* τ *and decreasing in* ε.

Proof. See appendix B2. ■

When environmental infrastructures are sufficiently efficient, the growth rate of the quality is positively linked to the economic growth rate. This is the reason why setting the instruments so as to maximize economic growth also yields the maximal growth rate for the environmental quality. Raising the tax rate increases the level of environment quality in each period as long as $\tau < \tau^*$. Further, increasing the share of polluting infrastructures improves the environmental quality in each period if and only if $\varepsilon < \varepsilon^*$.[15] When environmental infrastructures fail to offset the damages caused by physical capital and polluting infrastructures, economic and environmental assets go in opposite directions: their respective growth rate are inversely linked. In this case, growth-maximizing policy instruments are those associated with the fastest degradation

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[15] Note that a higher growth rate of the environment along the BGP translates into a higher level of environment quality in each period.

of the environment. The effects of the policy goes in the opposite way. In between these two cases there exists an intermediate case where increasing the tax rate improves the environmental quality. The decision to produce more infrastructures is undertaken at the expense of capital accumulation. Consequently, it translates into a lower ratio between physical capital and infrastructures. A substitution occurs in the productive combination against the polluting capital and in favor of public infrastructures, some of them being polluting, the others being environmental friendly. Nevertheless, the overall effect of increasing the provision of infrastructures is now beneficial to the environmental. In addition, of course, more environmental infrastructures would lead to a higher environmental quality.

It is key for our purpose to stress the following. When $\rho \geq \phi + \delta$ and $\varepsilon \geq \varepsilon^*$, then increasing the share of public expenditures devoted to environmental infrastructures is a means to enhance both growth and environment quality. Therefore, a policy dedicated to the provision of green infrastructures can provide a double dividend to the economy if these infrastructures are under-provisioned in the economy.

6 Optimal policy

In the previous section, the impact of public policy on growth and the environment has been investigated. In particular, we have identified the policy instruments that yield the highest economic growth rate and the best environmental quality along the BGP. There is no reason why such a specific policy would yield the highest welfare possible. In this section we will consider an alternative policy that precisely consists in maximizing welfare. The interesting point will be to compare the value of the policy instruments as well as the effects of an economic stimulus plan in the two cases.

6.1 Welfare maximizing policy

Let us first determine the value of the policy instruments when the policy maker behaves as a welfare maximizer.

By substituting the equilibrium decision (11) and the expression of environmental quality into preferences, the indirect utility function is given by:

$$V(K_t, G_t, \tau_t, \varepsilon_t) = \left\{ \begin{array}{l} \ln(1-\tau_t) + (\sigma - \eta\delta)\ln\varepsilon_t + (1-\alpha-\sigma+\eta\rho)\ln(1-\varepsilon_t) + \\ +(1-\alpha+\eta(\rho-\delta))\ln G_t + (\alpha-\eta\phi)\ln K_t + \gamma \end{array} \right\},$$

where γ is a constant. Hereafter, in order to have a interior solution for the instrument ε, we assume $\sigma \geq \eta\delta$ that is, the contribution of polluting infrastructures to production is higher than the environmental damage associated with their use. Otherwise producing polluting infrastructures creates a cost that outweights the benefit they generate and the government would choose $\varepsilon = 0$. In the same vein, and for the problem to be economically relevant, we also assume $1-\alpha+\eta(\rho-\delta) > 0$ and $\alpha > \eta\phi$.

Assume that $\sigma+\theta = 1-\alpha$,[16] then the optimal policy is defined as the sequence of instruments $\{\tau_t, \varepsilon_t\}_{t=0}^{+\infty}$ that maximizes the discounted sum of per-period indirect utilities, given the private

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[16] Hereafter, attention is paid to situations where the economy may follow a BGP. We further impose $1+\eta(\rho-\delta-\phi) \geq 0$ (see Proposition 2-*ii*) in order for any equilibrium path, associated with the optimal policy, to be sustainable.

and public capitals dynamics:

$$\max_{\{\tau_t,\varepsilon_t\}} \sum_{t=0}^{+\infty} \beta^t V(K_t, G_t, \tau_t, \varepsilon_t) \ ,$$

$$s.t \begin{cases} K_{t+1} = \beta\alpha(1-\tau_t)A\varepsilon_t^{\sigma}(1-\varepsilon_t)^{1-\alpha-\sigma}G_t^{1-\alpha}K_t^{\alpha} \\ G_{t+1} = \tau_t A\varepsilon_t^{\sigma}(1-\varepsilon_t)^{1-\alpha-\sigma}G_t^{1-\alpha}K_t^{\alpha} \\ K_0, G_0 \text{ given.} \end{cases}$$

Proposition 5 *The optimal policy consists of the following pair of instruments:*

$$\tau^o = \beta(1-\alpha) + \frac{\beta(1-\beta)\eta(\rho-\delta)}{1+\beta\eta(\rho-\delta-\phi)} \ , \tag{16}$$

$$\varepsilon^o = \frac{\sigma}{1-\alpha} - \frac{(1-\beta)\eta(\sigma\rho + (1-\alpha-\sigma)\delta)}{(1-\alpha)(1-\alpha+\eta((1-\beta\alpha)(\rho-\delta-\phi)) + (1-\beta)\phi))} \ . \tag{17}$$

Proof. see appendix C. ■

The first component of the tax rate corresponds to the optimal policy in the case where there are only productive infrastructures and no pollution: the higher the impact of infrastructures in production, the higher the tax rate and the provision of the public good (as in Glomm and Ravikumar 1994). That part differs from the growth maximizing tax rate mainly because there exists a one-period lag between public investment and the availability of infrastructures. The lower the degree of impatience (higher discount factor) the higher the tax rate and the public investment.

When taking into account the environmental dimension, the tax rate is augmented with a second term that reflects the net effect of infrastructures on the quality of the environment. What matters for determining how this additional term affects the tax rate is the overall contribution of both kinds of infrastructures on environmental quality. For instance, when this contribution is positive ($\rho > \delta$), the second component is positive, and consequently the optimal tax is higher than the growth maximizing tax. The opposite is true when $\rho < \delta$. In addition, assuming $\rho > \delta$, we can observe that the more the agent cares about the environment (η) and/or the higher the damage from capital (ϕ), the higher the tax rate and the amount of resources devoted to public spending.[17]

As for the optimal sharing of public expenditures between environmental and polluting infrastructures, it turns out that the share of polluting infrastructures is still increasing with their contribution to production. Indeed, the first term in (17) coincides with the growth maximizing share. But the polluting nature of these expenditures is now also taken into account. It calls for a reduction of public investments in polluting infrastructures with respect to the case where the environmental dimension is ignored (*i.e.* the growth-maximizing policy). In turn, it tends to promote the provision of environmental infrastructures.

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[17] Note also that owning more efficient environmental infrastructures (a higher $\rho - \delta$) is not necessarily an incentive to produce more public capital. Indeed,

$$\frac{\partial \tau^o}{\partial(\rho-\delta)} \gtreqless 0 \leftrightarrow 1 \gtreqless \beta\eta\phi$$

6.2 Comparing growth and welfare maximizing policies

This section focuses on the analysis of the impact of both policy regimes on growth and the environment.[18]

The comparison in terms of economic growth directly follows from proposition 3. Because $\{\tau^o, \varepsilon^o\} \neq \{\tau^*, \varepsilon^*\}$, the optimal growth rate is necessarily lower than the maximum achievable rate.

Comparing the effects of the two policies on environmental quality requires at first to consider the ranking between ρ, on the one hand, and $\phi + \delta$, on the other hand. Indeed, when $\rho > \phi + \delta$, proposition 2 tells us that environmental quality also follows a BGP and grows at a constant rate that is positively related to the growth rate of consumption, capital and infrastructures. This implies that under the growth maximizing policy, the growth rate of the environment is also too high. In sum, a policy that maximizes the growth rate of consumption and the environment is not optimal. When $\rho = \phi + \delta$, the quality of the environment is constant and the comparison between the environmental quality reached in each case is less straightforward. Here, we also need to refer to the comparison between growth and utility maximizing taxes since, according to proposition 4, environmental quality is increasing in τ but decreasing in ε. Straightforward calculations yield the following equivalence:

$$\begin{array}{ccccccl} \tau^o & \geq & \tau^* & \leftrightarrow & \beta\alpha(\rho-\delta) & \geq & (1-\alpha)(1-\beta\eta\phi) \quad \text{(case I)} \\ & < & & & & < & \qquad\qquad\qquad\qquad\quad \text{(case II)} \end{array} \tag{18}$$

In case I, the optimal policy leads to a lower economic growth and a higher quality than what would prevail with the growth maximizing policy. This is the more intuitive conclusion. Let us now investigate more deeply situations where the optimal tax rate is lower than the growth maximizing one. In case II, an economy that seeks to maximize growth produces too many infrastructures because: (*i*) the net effect of infrastructures on the environment is low or negative, (*ii*) the environmental concern is weak, (*iii*) the environmental damage due to capital is low, (*iv*) the economy is composed of impatient agents.

The optimal policy is associated with both a lower tax and a lower share of polluting infrastructures regarding the situation where consideration is only paid to growth ($\tau^o < \tau^*$, $\varepsilon^o < \varepsilon^*$). The overall effect on the environment is thus undetermined and it may be that giving priority to growth is favourable to the quality of the environment, which is not optimal. Table 1 provides a numerical example of such a case.

These results (obtained when $\rho > \phi + \delta$ and when $\rho = \phi + \delta$ in case II) challenge the widespread belief that more economic growth and a higher environmental quality is necessarily better for welfare. Suppose that $\rho \geq \phi + \delta$, then the following logic applies. Investment is required for growth, which is good for future consumption and which is likely to be also good for environmental quality. However, it comes at the expense of current consumption. Actually, by focusing primarily on growth, initial consumption will be lower than the optimal level and the resulting higher growth may be insufficient to fill this initial gap in the short and medium terms. Current and close-to-present consumptions are those that are valued the more under the discounted criterion used to assess the optimal policy. In addition, the higher level of environmental quality may not suffice to compensate for the initial sacrifice in terms of consumption. These arguments together explain why more growth and more environmental quality does not necessarily lead to a higher intertemporal welfare level.

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[18] Let us recall that, since both policies are associated with constant policy instruments, in either case the economy directly settles on a BGP.

Table 1: Comparison between growth-maximizing and optimal policy, when $\rho = \phi + \delta$ (Parameters value: $\beta = 0.95$, $\alpha = 0.45$, $\sigma = 0.366$, $\theta = 0.184$, $\phi = 0.2$, $\delta = 0.1$, $\rho = 0.3$, $\eta = 0.5$. Time horizon: 100 periods)

	Growth-maximizing policy	Optimal policy
τ	0.550	0.527
ε	0.665	0.655
χ	1.087	1.085
V	38.683	39.310
Q	0.925	0.918

6.3 The effects of stimulating the provision of environmental infrastructures

Let us now reassess the main question addressed in this paper. Can a public policy consisting of the stimulating environmental infrastructures succeed in promoting growth and welfare?

In section 5, we have identified situations where increasing the share of environmental infrastructures was a means to stimulate growth. According to the previous discussion, it is clear that a policy consisting of the financing of environmental infrastructures programs does not necessarily increase welfare. The question that naturally follows is whether there are conditions that ensure such a policy to be welfare improving. The answer is provided by assessing how the optimal policy objective and the growth rate evolve in response to changes in the share of green infrastructures in public expenditures. Actually, it is easily checked that the discounted sum of per-period utilities is single-peaked with respect to ε (see the appendix C). Moreover, we have shown in the appendix B that the same feature holds for the economic growth rate. Finally, we know that the optimal policy target reaches its maximum value for a ε lower than the one that provides the economy with the higher growth rate ($\varepsilon^o < \varepsilon^*$). This means that, when starting with few little environmental infrastructures (i.e. $\varepsilon > \varepsilon^*$), then increasing their share in public expenditures will allow the economy to experience both a higher growth rate and a higher welfare level.

7 Conclusion

This paper studies the relationship between infrastructures, growth and the environment. Rather than globally assessing the impact of infrastructures on macroeconomic performance and the environment, we choose to decompose this public capital into polluting and environmental infrastructures. Having first characterized the competitive equilibrium and its sustainable balanced growth path, we then focus on the design of the public policy when two different and potentially conflicting goals may be pursued: maximizing growth vs. maximizing welfare. Beyond the traditional question of how many resources should an economy devote to the provision of infrastructures, we further investigate how the overall amount of public expenditures should be divided between the two kinds of infrastructures. Our main conclusion is the following. For an economy that has already invested a lot in productive, but polluting, infrastructures, increasing the share of public resources devoted to environmental infrastructures is a means not only to promote growth but also to improve welfare. In other words, for this kind of economy, any efficient economic stimulus plan should consist in giving priority to the production of a greener public capital.

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Appendix

A Existence of a $\pi-$CE (prop. 1)

The Hamiltonian associated with the artificial planning problem (10) reads as:

$$H\left(c_t, K_t, \lambda_{t+1}\right) = \beta^t \left(\ln c_t + \eta \ln Q_t\right) + \lambda_{t+1}((1-\tau_t)AG_{pt}^{\sigma}G_{et}^{\theta}K_t^{\alpha} - c_t) \ ,$$

where λ_{t+1} is the shadow price of the resource constraint.

The first order conditions are:

$$\frac{\partial H}{\partial c_t} = 0 \quad \Leftrightarrow \quad \frac{\beta^t}{c_t} = \lambda_{t+1} \ , \tag{19}$$

$$\lambda_t = \frac{\partial H}{\partial K_t} \quad \Leftrightarrow \quad \lambda_t = \lambda_{t+1}(1-\tau_t)\alpha AG_{pt}^{\sigma}G_{et}^{\theta}K_t^{\alpha-1} \ . \tag{20}$$

Following Glomm and Ravikumar (1994) let us postulate, and afterwards confirm, that optimal decisions are linear functions of the after tax income. In particular

$$c_t = m(1-\tau_t)AG_{pt}^{\sigma}G_{et}^{\theta}K_t^{\alpha} \ , \tag{21}$$

Substituting (19) into (20) yields:

$$c_t = \beta\alpha(1-\tau_t)AG_{pt}^{\sigma}G_{et}^{\theta}K_t^{\alpha-1}c_{t-1}$$

and the expression of the investment decision at period t directly follows from our guess (21):

$$K_{t+1} = \beta\alpha(1-\tau_t)AG_{pt}^{\sigma}G_{et}^{\theta}K_t^{\alpha}\ .$$

Together with the bugdet constraint, the consumption decision:

$$c_t = (1-\beta\alpha)(1-\tau_t)AG_{pt}^{\sigma}G_{et}^{\theta}K_t^{\alpha}\ .$$

The last two expressions correspond to (11) and (12) given in the text. Arguments for showing that the pair (11) and (12) is the only solution to the artificial problem can be found in the appendix related to the second proposition of Glomm and Ravikumar (1994). The equivalence between the solution of the artificial problem and the competitive equilibrium is the statement of their first proposition.

B Balanced and sustainable growth

B.1 Existence of a Sustainable growth path (prop. 2)

Equations (9) and (12) define the dynamical system in terms of $\{G_{pt}, G_{et}, K_t\}$. Now, with the rule for the sharing of public expenditures between the two types of infrastructures, equilibrium dynamics simplify to:

$$\begin{cases} K_{t+1} = \beta\alpha(1-\tau_t)A\varepsilon_t^{\sigma}(1-\varepsilon_t)^{\theta}G_t^{\sigma+\theta}K_t^{\alpha} \\ G_{t+1} = \tau_t A\varepsilon_t^{\sigma}(1-\varepsilon_t)^{\theta}G_t^{\sigma+\theta}K_t^{\alpha} \end{cases}$$

Using this system to compute the equilibrium ratio between K and G, we get:

$$\frac{K_{t+1}}{G_{t+1}} = \frac{\beta\alpha(1-\tau_t)}{\tau_t}$$

and note that, under a constant taxation regime, there is no transitional dynamics since this ratio is constant.

Now assume the technology exhibits constant returns to private capital and public infrastructures, that is, $\theta = 1-\alpha-\sigma$ and denote $x_t = \frac{K_t}{G_t}$ and $\chi_K = \frac{K_{t+1}}{K_t}$ (resp. $\chi_G = \frac{G_{t+1}}{G_t}$). Showing the existence of a balanced growth path boils down to finding the pair (x, χ) that solves the following system:

$$\begin{cases} \chi = \beta\alpha(1-\tau)A\varepsilon^{\sigma}(1-\varepsilon)^{1-\alpha-\sigma}x^{\alpha-1} \\ \chi = \tau A\varepsilon^{\sigma}(1-\varepsilon)^{\theta}x^{\alpha} \end{cases}$$

Direct calculations provide the equilibrium ratio and growth factor:

$$x = \frac{\beta\alpha(1-\tau)}{\tau} \tag{22}$$

$$\chi = (\beta\alpha(1-\tau))^{\alpha}\tau^{1-\alpha}A\varepsilon^{\sigma}(1-\varepsilon)^{1-\alpha-\sigma} \tag{23}$$

For growth to be sustainable, utility must be non decreasing in the long run. Environmental quality in equilibrium is defined as:

$$Q_t = (\varepsilon)^{-\delta}(1-\varepsilon)^{\rho}x^{-\phi}G_t^{\rho-\delta-\phi}$$

and its growth factor is a function of χ: $\frac{Q_{t+1}}{Q_t} = \chi_{Q_t} = \chi^{\rho-\delta-\phi}$. Consumption grows at the same rate than K and G: $\frac{c_{t+1}}{c_t} = \chi$. Now we must have $U_{t+1} - U_t \geq 0$ which is equivalent to:

$$\ln\left(\frac{c_{t+1}}{c_t}\right) + \eta \ln\left(\frac{Q_{t+1}}{Q_t}\right) \geq 0 \Leftrightarrow (1 + \eta(\rho - \delta - \phi) \ln \chi \geq 0$$

thus the condition in proposition 2.

As for the evolution of Q_t, in order for Q to be not decreasing, one has to impose: $\rho-\delta-\phi \geq 0$. Assuming $\delta = \rho - \phi$ then environmental quality is constant and equal to:

$$Q = \left(\beta\alpha\frac{(1-\tau)}{\tau}\right)^{-\phi} \varepsilon^{-(\rho-\phi)}(1-\varepsilon)^{\rho} \ . \tag{24}$$

otherwise it tends to 0 as G goes to infinity.

B.2 Comparative statics (prop. 3, 4)

First we consider the impact of a change in the instruments on the growth rate. Take the derivative of the growth factor with respect to τ, one finds

$$\frac{\partial \chi}{\partial \tau} \geq 0 \leftrightarrow \tau \leq 1 - \alpha.$$

Now, the derivation with respect to ε yields:

$$\frac{\partial \chi}{\partial \varepsilon} \geq 0 \leftrightarrow \varepsilon \leq \frac{\sigma}{1-\alpha}$$

thus the statement in proposition 3.

Next we analyze how (the growth factor of) environmental quality changes in response to a change in either the tax rate or the sharing rate.

- When $\rho \neq \delta + \phi$, the derivative of growth factor of the environment with respect to each instrument is: $\frac{\partial \chi_Q}{\partial j} = (\rho - \delta - \phi)\frac{\partial \chi}{\partial j}\chi^{\rho-\delta-\phi-1}$ for $j = \tau, \varepsilon$. Therefore,

$$\begin{array}{c} \frac{\partial \chi_Q}{\partial \tau} \geq 0 \leftrightarrow \tau \leq (\geq) 1 - \alpha \text{ if } \rho > (<) \delta + \phi \\ \frac{\partial \chi}{\partial \varepsilon} \geq 0 \leftrightarrow \varepsilon \leq (\geq) \frac{\sigma}{1-\alpha} \text{ if } \rho > (<) \delta + \phi \end{array}$$

- For the case where $\rho = \delta + \phi$, derivating equation (24) with respect to τ and ε, we obtain:

$$\frac{\partial Q}{\partial \tau} = \frac{\phi}{\tau}\left(\beta\alpha\frac{(1-\tau)}{\tau}\right)^{-\phi} \varepsilon^{-(\rho-\phi)}(1-\varepsilon)^{\rho} > 0$$

$$\frac{\partial Q}{\partial \varepsilon} = -\left(\beta\alpha\frac{(1-\tau)}{\tau}\right)^{-\phi} \varepsilon^{-(\rho-\phi)-1}(1-\varepsilon)^{\rho-1}((\rho-\phi)(1-\varepsilon) + \rho\varepsilon) < 0$$

thus the statement in proposition 4.

C Optimal policy instruments (prop. 5)

Using dynamic programing tools, we define $v(K_t, G_t)$ as the value function associated with the government's optimization program. In the ln/Cobb-Douglas framework at hand, it makes sense to guess the following form for $v(K_t, G_t)$:

$$v(K_t, G_t) = a + b \ln K_t + c \ln G_t,$$

with a, b and c three constants to be determined. The government instruments at date t solve the Bellman equation:

$$v(K_t, G_t) = \max_{\tau_t, \varepsilon_t} \left\{ V(K_t, G_t, \tau_t, \varepsilon_t) + \beta v(K_{t+1}, G_{t+1}) \right\},$$

$$\text{where } \begin{cases} K_{t+1} = \beta\alpha(1-\tau_t)A\varepsilon_t^\sigma(1-\varepsilon_t)^{1-\alpha-\sigma}G_t^{1-\alpha}K_t^\alpha \\ G_{t+1} = \tau_t A\varepsilon_t^\sigma(1-\varepsilon_t)^{1-\alpha-\sigma}G_t^{1-\alpha}K_t^\alpha \end{cases}$$

The first order conditions for the maximization of the r.h.s. of the Bellman equations yields the solutions:

$$\tau = \frac{\beta c}{1+\beta(b+c)} \text{ and } \varepsilon = \frac{\sigma(1+\beta(b+c)) - \eta\delta}{(1-\alpha)(1+\beta(b+c)) + \eta(\rho-\delta)} \tag{25}$$

Inserting those expressions into the Bellman equation, and because those equations hold for any values of the stock variables, identification of similar terms ends up in the following system of equations:

$$\begin{aligned} b &= \alpha(1+\beta(b+c)) - \eta\phi \ , \\ c &= (1-\alpha)(1+\beta(b+c)) + \eta(\rho-\delta) \ . \end{aligned}$$

Solving this system in $\{b, c\}$, one obtains:

$$\begin{aligned} b &= \frac{(1-\beta(1-\alpha))(\alpha-\eta\phi) + \beta\alpha(1-\alpha+\eta(\rho-\delta))}{1-\beta} \ , \\ c &= \frac{(1-\beta\alpha)(1-\alpha+\eta(\rho-\delta)) + \beta(1-\alpha)(\alpha-\eta\phi)}{1-\beta} \ . \end{aligned}$$

Finally, substituting those expressions into (25), one finds the optimal solutions

$$\tau^o = \frac{\beta(1-\alpha) + \beta\eta((1-\beta\alpha)(\rho-\delta) - \beta(1-\alpha)\phi)}{1+\beta\eta(\rho-\delta-\phi)} \ ,$$

and

$$\varepsilon^o = \frac{\sigma(1+\beta\eta(\rho-\delta-\phi)) - \delta\eta(1-\beta)}{(1-\alpha)(1+\beta\eta(\rho-\delta-\phi)) + \eta(\rho-\delta)(1-\beta)} \ .$$

Direct calculations yield (16) and (17).

Assume $\rho = \phi + \delta$, the last part of this appendix shows that the discounted sum of utilities

- first is finite under a constant optimal policy, even if both capital and infrastructures follow a BGP (that is, an explosive path),

- second is bell-shaped or single-peaked with respect to ε.

The trajectory of consumptions $\{c_t\}_{t=0}^\infty$ is given by: $c_t = \chi^t c_0$ with χ the growth factor and

$$c_0 = (1-\beta\alpha)(1-\tau)A\varepsilon^\sigma(1-\varepsilon)^{1-\alpha-\sigma}x^{\alpha-1}K_0$$

Environmental quality is constant over time:

$$Q = \varepsilon^{-\delta}(1-\varepsilon)^{\rho}x^{-\phi}$$

thus,

$$\sum_{t=0}^{\infty}\beta^t U_t = \sum_{t=0}^{\infty}\beta^t\left(t\ln\chi + \ln c_0 + \eta\ln Q\right)$$

which is equivalent to

$$\sum_{t=0}^{\infty}\beta^t U_t = \frac{\ln c_0 + \eta\ln Q}{1-\beta} + \ln\chi\sum_{t=0}^{\infty}\beta^t t \tag{26}$$

since $\sum_{t=0}^{\infty}\beta^t t$ is finite (and equal to a constant Ψ to be determined later), the discounted sum of utilities is finite as well.

Now, rewrite (26) as a function of ε, direct calculations yield:

$$\sum_{t=0}^{\infty}\beta^t U_t = \left(\frac{\sigma-\eta\delta}{1-\beta} + \Psi\sigma\right)\ln\varepsilon + \left(\frac{1-\alpha-\sigma+\eta\rho}{1-\beta} + \Psi(1-\alpha-\sigma)\right)\ln(1-\varepsilon) + \text{constant}$$

Maximizing this expression with respect to ε yields the following unique constant share :

$$\varepsilon = \frac{\sigma-\eta\delta+(1-\beta)\Psi\sigma}{1-\alpha+\eta(\rho-\delta)+(1-\beta)\Psi(1-\alpha)}$$

which must be equal to ε^0, which gives $\Psi = \frac{\beta}{(1-\beta)^2}$.

The optimal policy objective is thus finite and single-peaked with respect to ε.

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