



UNIVERSITY OF  
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# Essays on Economic Activity and the Environment

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To my husband and mother

# Essays on Economic Activity and the Environment

by

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## Abstract

This thesis consists of three essays on the nexus between economic activity and the environment and addresses issues such as growth, crime, and environmental quality. Chapter 1 investigates the relationship between human capital accumulation and health damaging pollution. It is shown that global dynamics are featured by a path dependency. There is either cyclical convergence to a low income equilibrium or positive long-run growth with an Environmental Kuznets Curve, depending on the initial conditions with respect to human capital. Also, as far as the evidence is concerned, the model gives an empirically relevant correlation between the volatility of income and the mean value of income. Chapter 2 focuses on a relatively unexplored theme of the economics literature, linking criminal activity and pollution. An emission tax motivates firms to invest in pollution abatement technologies, but at the same time this type of investment is discouraged by the presence of criminal groups, whose main activity is money extortion. It is observed that under certain parameter values, there exists a situation in which a higher crime economy will produce lower output and nevertheless will have higher pollution. In other words, it is proved that crime might be one of the explanatory factors for which countries with lower output (i.e., less developed countries) are more polluted. In the last chapter, we examine the effects of the imposition of a minimum quality standard on firm's quality choices, when the policy maker is at an informational disadvantage regarding the monopolist's cost structure. In this asymmetric information environment, it is shown that if the regulator is outsmarted by the firm's misleading signal, the minimum quality standard will be downward distorted, which might negatively affect social welfare.

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# Contents

<b>Contents</b>	<b>iv</b>
<b>List of Figures</b>	<b>vi</b>
<b>Introduction</b>	<b>1</b>
<b>1 Health, Economic Growth and the Environmental Kuznets Curve</b>	<b>3</b>
1.1 Introduction . . . . .	3
1.2 The Model . . . . .	8
1.2.1 Households . . . . .	8
1.2.2 Production . . . . .	10
1.2.3 Pollution . . . . .	11
1.3 Equilibrium . . . . .	12
1.4 Steady state analysis and dynamics . . . . .	13
1.5 Conclusion . . . . .	15
<b>2 Crime and pollution</b>	<b>17</b>
2.1 Introduction . . . . .	17
2.2 The Model . . . . .	22
2.2.1 Entrepreneurs . . . . .	23
2.2.2 Households . . . . .	27
2.2.3 The dynamic equilibrium . . . . .	31
2.3 Extension . . . . .	32
2.3.1 Entrepreneurs . . . . .	33
2.3.2 Households . . . . .	35
2.3.3 The dynamic equilibrium . . . . .	37
2.3.4 The effect of crime on the environment . . . . .	38
2.4 Conclusion . . . . .	40
<b>3 Minimum Quality Standards under Asymmetric Information</b>	<b>42</b>
3.1 Introduction . . . . .	42
3.2 The Model . . . . .	47
3.3 Analysis . . . . .	49
3.3.1 Unregulated market equilibrium . . . . .	49
3.3.2 First-Best . . . . .	49
3.3.3 Second-Best . . . . .	50
3.3.4 Regulated market equilibrium with asymmetric information . . . . .	51
3.4 Conclusion . . . . .	57

<b>Conclusion</b>	<b>58</b>
<b>4 Appendices</b>	<b>61</b>
4.1 Appendix to chapter 1 . . . . .	61
4.1.1 Proof of lemma 1 . . . . .	61
4.2 Appendix to chapter 3 . . . . .	64
4.2.1 Welfare analysis example . . . . .	64
<b>Bibliography</b>	<b>65</b>

# List of Figures

1.1	Phase diagram for $h_t$ and $\mu_t$ . . . . .	14
2.1	Environmental Quality in Developed and Developing Countries . . . .	21
2.2	Phase diagram for $\epsilon_{t+1}$ and $\epsilon_t$ . . . . .	30
2.3	Phase diagram for $\epsilon_t$ and $\epsilon_{t+1}$ . . . . .	31
2.4	A numerical example for $\Delta P > 0$ . . . . .	40

# Introduction

In the quest for a better comprehension of the determinants of the “quality of life”, the physical environment is being given increasing attention as one of the crucial factors influencing people’s physical, mental and social well-being. It is a well-known fact that people nowadays face an environment hostile to their aspirations for a better life. Who is to blame? It is man’s economic activities which include the excessive production and consumption of goods. More precisely, the inefficient and dirty methods of production, and incautious and thoughtless disposal of post-consumption waste are the main contributors to environmental degradation, which can possibly lead to economic and ecological collapse in the long-run. The impact of the deterioration of the environment (e.g. air pollution, noise, climatic factors) is evident from its direct and indirect negative effects on human health, both physical and mental. For example, air pollution, which is a by-product of human activities, may result in serious health conditions like cancer or other types of reproductive and birth defects. It is crucial to understand the environmental impacts upon quality of life, and increase the efforts for the amelioration of the effects caused by anthropogenic pollution, either through individual action or mainly through the implementation of well-drawn policy measures. This thesis presents three distinct chapters on the link of various aspects of economic activity and the environment.

The first chapter builds a model in which the dynamics of pollution and human capital accumulation interact and consequently are jointly defined. Although human capital accumulation is considered as one of the main determinants of growth, this is not always the case in our model since the occurrence of pollution is pivotal. It is shown that when the effect of income on pollution is positive and monotonic, the impact of pollution on health can negatively influence the dynamics of the economy and this occurs for lower levels of human capital (or low income economies). After

a certain threshold, the existence of an Environmental Kuznets Curve shows that as income increases, pollution will eventually decrease which means that health will be consequently improved. This will reinforce the positive effect of current income on future income and possibly lead to growth. Given the pollution's effect on human capital accumulation and growth, it is demonstrated that the economy's development path will depend critically on the initial values with respect to human capital.

The second chapter investigates the sources of crime persistence and their implications for an economy's environmental quality. We built a model in which firms' endogenous technology choice, is simultaneously driven by an environmental tax and the presence of criminal activity. The introduction of an intergenerational externality in the determination of cultural norms and moral values, is an underlying source of dynamics which explains the incidence of criminality among individuals. We find that crime will converge to a long-run equilibrium where its magnitude can be either low or high, depending on whether the economy's initial conditions regarding the number of criminals lies below or above a certain threshold and this might have a negative outcome on the environment. We show that there exist circumstances under which a high crime economy, that produces less, actually has higher pollution.

Chapter 3 studies the effects of imposing a minimum quality standard (MQS) on a monopolistic economy in which the firm faces quality-dependent fixed costs that are its private information. It is shown that, in this asymmetric information setting, the presence of the MQS-setting regulator creates negative impacts on quality options which ultimately distort the optimal quality choice. The rationale behind this is that firms may have an incentive to decrease their quality levels in order to signal to the regulator that it is too costly to increase quality. If the regulator doesn't receive any informative signal, the MQS will be downward distorted, which might eventually affect social welfare. The policy implication of our result is that, under certain circumstances, the regulator may optimally choose to pre-commit not to regulate, as in this case social welfare could be higher than in the scenario where the regulator is free to step in.

# Chapter 1

## Health, Economic Growth and the Environmental Kuznets Curve

### 1.1 Introduction

Notwithstanding the fact that environmental problems, like pollution, have gained great prominence during the last decades, the demand for investing in environmental improvement is sometimes overshadowed by the argument that environmental policy harms the economy. Particularly, there are concerns that a reduction in production and economic growth might be necessary. However, the detrimental impact of pollution on health and the fact that impaired health affects growth negatively, which is well established by various researchers, can make someone reconsider the benefits of environmental enhancement.

In this paper, we aim to study the impact of pollution on the dynamics of the economy when it affects the health of agents. There exists a great number of empirical papers that support the negative effects of environmental pollution on individuals' health. Many cohort studies (e.g., Dockery et al. (1993), Pope III et al. (1995) and Pope III et al. (2002)) and daily time series studies (e.g. Samet et al. (2000) and Daniels et al. (2000)) have recorded the short and long-term effects of air pollution on respiratory and cardiovascular illness and the related morbidity and mortality consequences. These health repercussions have also been verified in country-specific studies (e.g. Evans and Smith (2005), Kan et al. (2008)). However, the implications are not restricted to impaired health and life expectancy. There are papers that

associate damaged health with individuals' learning ability and provide evidence about the harmful effects of pollution on individuals' cognitive development and performance. Margulis (1991) discovers considerable empirical correlation between lead in air and blood lead levels and points out that children with higher blood lead levels have a lower cognitive development and need complementary education. Freire et al. (2010) detect that traffic-related air pollution may have a detrimental impact on children's neurodevelopment, even at low exposure levels. Lavy et al. (2014) find that short term exposure to either fine particulate matter or carbon monoxide is detrimental to health and human capital formation and has direct impact on cognitive performance.

A significant number of previous theoretical work link the deterioration of the environment to economic growth (e.g. Smulders and Gradus (1996), Hettich (1998), Grimaud (1999), Grimaud and Tournemaine (2007)). Some papers of the aforementioned literature like Grimaud (1999), and Grimaud and Tournemaine (2007) presume that pollution is a function of the aggregate level of output, and this is the case for our model as well. Furthermore, there is another group of literature that investigates how human capital accumulation can affect economic growth (e.g. Lucas (1988), Rebelo (1990), Caballé and Santos (1993), Greiner and Semmler (2002), Alonso-Carrera and Freire-Serén (2004) etc.). It was Lucas (1988) seminal work that influenced the majority of this literature. His model has been extended and developed further by many authors. The basic concept is that human capital accumulation is considered endogenous and one of the main determinants of the growth rate.

Lucas (1988) model has also been the basic framework of some papers belonging to a literature that combines the two aforementioned strands, namely it relates the environmental degradation, through its negative effect on human capital, to economic growth. For example, in Gradus and Smulders (1993), environmental pollution can influence the learning ability of an individual that can have an impact on the optimal growth rate, which is quite similar to our assumptions of the present paper. The notion is that pollution affects workers' health which reduces their ability to learn. Another paper that argue that pollution, by affecting health, can have a direct effect on long-term performances are those of Van Ewijk and Van Wijnbergen

(1995) in which the accumulation of knowledge is obstructed by pollution. Pautrel (2008) finds that when pollution affects life expectancy, more pollution intensifies the frequency of replacement of generations, decreasing the accumulation of aggregate human capital and the long-run optimal growth rate.

Closely related to our paper is a body of theoretical literature that examines the interactions between environmental quality, health and economic growth in dynamic environments, by studying how pollution affects health through the mortality channel, without complete unanimity on the influence of an environmental policy on the economy and specifically on growth (Pautrel (2008), Varvarigos (2010), Jouvet et al. (2010), Mariani et al. (2010), Palivos and Varvarigos (2017), Raffin and Seegmuller (2014)). In particular, Varvarigos (2010) analyses the extent to which multiple steady state equilibria and poverty traps can be ascribed to a certain degree to the presence of a two-way effect between the quality of the environment and economic activity. Jouvet et al. (2010) study a two period overlapping generations (OLG) model in which longevity depends positively on private health expenditure but negatively on pollution and present a scheme of optimal policies on income and health spending. Mariani et al. (2010) derive a positive correlation between longevity and environmental quality. Their model allows for multiple steady state equilibria where low life expectancy coexists with low environmental quality. Human capital accumulation is also introduced to their benchmark model and they find that the aforementioned correlation still holds and extends to income in the long-run (and under some conditions to human capital as well). Raffin and Seegmuller (2014) analyse the interaction between pollution and economic growth when longevity is endogenously determined by both environmental quality and public health policies. While economic growth generates negative externalities to the environment, it can also increase available resources for investments, such as health spending and abatement policies and therefore enhance life expectancy. Multiple steady states are derived: a poverty trap with high pollution and short life expectancy and a high growth rate equilibrium with low pollution and longer life expectancy. Raffin and Seegmuller (2017) consider an overlapping generations model where pollution, public health expenditure and private health efforts undertaken by individuals are all determinants of longevity. They underline the destabilising role of pollution on the

dynamic behavior of the economy and highlight the occurrence of both structural instability and endogenous cycles. The most relevant paper of this strand of literature is the Palivos and Varvarigos (2017) one, in which they employ an OLG model wherein mortality is associated with environmental quality and in which production is characterised by learning-by-doing externalities. They highlight the role of an active pollution abatement policy as an aid to the economy to avoid poverty traps and therefore as an engine for long-run growth. In relation to our results, Palivos and Varvarigos (2017) find either limit cycles or long-run growth depending on the distribution of public spending devoted to pollution abatement.

Another issue that is pertinent to the interactions between growth and the environment is the topic of the Environmental Kuznets Curve (EKC) which graphs the hypothesis that as income increases at first pollution increases but, subsequently, pollution decreases (originally demonstrated by Grossman and Krueger (1994)). Explanations for this relation between income and pollution have been several, like the notion that as economies grow people become more environmentally aware and/or there are better abatement technologies, cleaner technologies, outsourcing of dirty production to developing countries etc., and our paper provides a complementary one. Evidence concerning the validity of the EKC is rather mixed. On the one hand, there are several empirical studies (e.g. Grossman and Krueger (1994), Shafik and Bandyopadhyay (1992), Panayotou et al. (1993) etc.) that support the inverted-U shaped relation between pollution level and per capita income (EKC). On the other hand, papers like Azomahou et al. (2006), find that greenhouse gasses (in particular  $CO_2$ ) exhibit an increasing - and even U (not inverted) shaped - relationship with growth. John and Pecchenino (1994) develop a model based on overlapping generations where agents accumulate capital and environmental quality and where pollution is generated by consumption and derive an inverse-V shape pollution-income relationship. By employing a static theoretical model, Andreoni and Levinson (2001) underpin that if abatement technology satisfies increasing returns to scale (i.e., the higher the pollution is before abatement, the lower the cost of abating one unit of pollution), pollution will exhibit an inverted-U shaped relationship with respect to income irrespective of the production function. Raffin and Seegmuller (2014) theoretical analysis also refers to the Environmental Kuznets Curve, as a pattern of

development, which is quite similar to our model and Mariani et al. (2010) mention that the dynamics of their model are consistent with the so-called EKC.

The implications of our results are, mainly, related to the papers of Andreoni and Levinson (2001), and Palivos and Varvarigos (2017). Similar to Andreoni and Levinson (2001), in our model, the flow of emissions and the abatement technology are such that an inverse-U-shaped relation between emissions and output is being generated. Yet, while for Andreoni and Levinson (2001) this is an indicator of an EKC, we show that this is not by itself sufficient for its existence. In our dynamic model, favourable initial conditions with respect to income are also needed. In Palivos and Varvarigos (2017), whenever there are endogenous cycles, the cycles appear on the high income equilibrium. However, this contradicts evidence on macroeconomic volatility and economic growth, which shows that the relation between income and volatility is negative (e.g. Ramey and Ramey (1995), Martin and Rogers (2000), Kroft and Lloyd-Ellis (2002)). In our model we show that, closer to the existing evidence, it is the low income equilibrium that is volatile, i.e., cycles occur at relatively low stages of development.

The basic set up is a dynamic model in which a type of investment (transmission of resources from now to the future via human capital accumulation) is influenced by the negative effect of pollution on health and in which the government provides resources for pollution abatement. Our contribution is twofold. On the one hand we find path dependency, namely, we either have cyclical convergence to a low income equilibrium or positive long-run growth with an EKC, depending on the initial conditions with respect to human capital. On the other hand, as far as the evidence is concerned, we can give an empirically relevant correlation between the volatility of income and the mean value of income. We show that the low income equilibrium is the one that will be volatile (with endogenous cycles) and the high income equilibrium is the one that will lead to growth.

The rest of the paper is organised as follows. In Section 1.2, we present the model and analyse the dynamics of human capital accumulation and pollution. In Sections 1.3 and 1.4, we derive the long-run equilibria, the steady states and examine their stability characteristics. Finally, Section 1.5 summarizes the results and concludes.

## 1.2 The Model

We employ a two-period overlapping generations model with discrete time, indexed by  $t = 0, 1, 2, \dots$ . The first period is childhood, which is a bit broader and includes the first adult years as well, and the second period is adulthood. At the end of the first period each agent gives birth to one child. We assume no population growth, so we have a constant population mass normalized to unity. During the first period of their lives agents devote effort in learning activities (education activities, research, general reading) and don't consume. When individuals get to choose their consumption, in the second period of their lives, they take into account their children's consumption as well. Then, during adulthood, agents supply their effective labour, earn labour income, consume and pass away naturally. We assume that individuals are endowed at birth with a stock of human capital ( $h_t$ ). So, when individuals begin the learning process they already have some human capital stock available, which is proportional to the human capital stock that was built by the previous generation. Namely, the knowledge of the previous generation gained through investment, passes as an externality to the next one, and the new generation will try to make additions on that knowledge, and so on.

### 1.2.1 Households

As we have already mentioned, during the first period of their lives ( $t$ ), agents are putting effort in education, in order to improve their human capital and incur a utility loss, and during the second period ( $t+1$ ) they gain utility from consumption. A similar formulation where there is a direct disutility from effort can be found in Blackburn and Varvarigos (2008) and Blankenau and Camera (2009) among others. An agent who is born in period  $t$  has the following lifetime utility:

$$u_t = -\Gamma_t e_t + \beta \ln c_{t+1}, \quad (1.1)$$

where  $e_t$  is the amount of effort for human capital,  $\Gamma_t$  gives the utility loss as a result of an additional unit of effort (i.e., is the marginal disutility of effort,  $\frac{\partial \Gamma_t e_t}{\partial e_t} = \Gamma_t$ ), and  $\beta \in (0, 1)$  is a parameter that quantifies the effect of consumption on utility (i.e., the discount factor).

We consider that the disutility of effort ( $\Gamma_t$ ) is an increasing function of the stock of pollution ( $\mu_t$ ):

$$\Gamma_t = \Gamma(\mu_t), \quad (1.2)$$

where  $\Gamma'(\mu_t) > 0$ . With this assumption, we capture the idea that pollution affects the individual's health conditions and cognitive abilities by increasing the effort required to achieve a given improvement in human capital.

We assume that the amount of effort for human capital is being translated into human capital improvement according to the following functional form:

$$h_{t+1} = \phi e_t h_t \quad (1.3)$$

where  $\phi > 0$ .<sup>1</sup> So,  $e_t h_t$  is the amount of time the individual spends on learning augmented by his existing stock of human capital. Together they create the input that adds to the future human capital stock ( $e_t h_t$  : effort in effective units).

Individual's consumption depends on his labour income. The individuals' labour income is in effective terms which means that he isn't just providing some of his time to his employer but his human capital as well. So, his labour income is how much human capital he possesses in period  $t + 1$  multiplied by his wage (of each unit of human capital) of the same period. Since, the individual isn't going to live one more period and doesn't have any incentive to leave any bequest, he will consume his entire income. Thus, his budget constraint is:

$$h_{t+1} w_{t+1} = c_{t+1} \quad (1.4)$$

which means that consumption is equal to income from effective labour.

The maximization of the individual's lifetime utility subject to (1.2), (1.3) and (1.4) yields the optimal amount of effort for human capital:

$$e_t = \frac{\beta}{\Gamma(\mu_t)}, \quad (1.5)$$

where  $\frac{de_t}{d\mu_t} < 0$ . The fact that the optimal amount of effort is decreasing in  $\mu_t$ , means that as pollution increases, the utility loss  $\Gamma(\mu_t)$  will be higher, so optimally

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<sup>1</sup>Later we will specify a further restriction on  $\phi$ .

the agent will reduce the amount of effort spent on human capital accumulation. Concurrently, - for given  $\Gamma(\mu_t)$  - a higher  $\beta$ , i.e., the higher the importance given to the second period, will lead to a higher  $e_t$ , i.e., the higher the effort exerted in the first one. Provided that the agent wants to consume more during the 2nd period of his life, he needs to bestir greater effort during the 1st period, so that more human capital to be generated. The increased human capital will ensure more income for the agent, which will lead him to increased consumption.

Finally, by substituting the optimal amount of effort into Eq. (1.3), the dynamics of human capital accumulation can be re-written as:

$$h_{t+1} = \frac{\phi\beta h_t}{\Gamma(\mu_t)} = H(\mu_t, h_t) \quad (1.6)$$

The economy grows via the accumulation of human capital, nevertheless there exist two mechanisms that affect the dynamics of the economy. There is the direct positive effect from the externality of the intergenerational transmission of human capital, that for given  $e_t$ , if the human capital of the current generation ( $h_t$ ) increases, then the human capital of the next generation ( $h_{t+1}$ ) will also be increased. And the indirect effect, that as pollution increases, due to its negative impact on agents' health and how this affects their decisions on how much time and effort they will devote to accumulate human capital, the accumulation of human capital will decrease.

### 1.2.2 Production

There is a unique final good (with price normalized to 1) which is produced by a mass of competitive firms (normalized to unity). Production technology is linear in effective labour and given by the following equation:

$$y_t = Ah_t, \quad (1.7)$$

where  $A$  is a fixed parameter (constant productivity of human capital).

Aiming at the improvement of environmental quality, the government attempts to decrease pollution by providing a public good, that is pollution abatement ( $g_t$ ), which is financed by a production tax. Firms pay a percentage  $T$  ( $0 < T < 1$ )

for every unit of output they produce. Government's revenues from the flat tax on production ( $TAh_t$ ), will be used to produce the public good in every period, so government's balanced budget is:

$$g_t = TAh_t \quad (1.8)$$

In a perfectly competitive labour market, where the price of labour, i.e. the wage, is given for all firms, the supply of labour is perfectly elastic. In equilibrium the wage should equal human capital productivity net of taxes, as a higher wage would drive labour demand to zero and therefore would fall short of labour supply, and a lower wage would drive labour demand to infinity and lead to excess demand since supply is finite. Firms profits are  $\pi = Ah_t - h_t w_t - TAh_t = h_t(A(1 - T) - w_t)$  and the wage per unit of effective labour is:

$$w_t = A(1 - T), \quad \forall t \quad (1.9)$$

So, labour income for every period is:

$$w_t h_t = A(1 - T)h_t \quad (1.10)$$

### 1.2.3 Pollution

Pollution is considered a by-product of firms' activities, which deteriorates agents' health and cognitive abilities. We assume that pollution is a stock variable which is described by a dynamic equation that associates today's pollution with tomorrow's pollution and has a flow of emissions as well, which result from production processes (the higher the production, the higher the emissions). Therefore, we define the law of motion of the pollution stock as:

$$\mu_{t+1} = \eta\mu_t + P_t \quad (1.11)$$

where  $P_t$  corresponds to the flow of emissions and  $\eta$  ( $0 < \eta < 1$ ) is a parameter denoting the fraction of pollutants that aren't naturally absorbed ( $1 - \eta$  being the fraction of pollutants that decays in every period).

The flow of emissions is assumed to be a function of production and pollution abatement,  $P_t = P(y_t, g_t)$ . Specifically, pollution flow increases with the increase in production activities,  $P_y > 0$ , and reduces with the governmental provision of abatement services,  $P_g < 0$ . Thus, the general form of the flow of emissions function can be written as:

$$P_t = \frac{py_t}{1 + f(g_t)} \quad (1.12)$$

where  $p$  are the emissions of each unit of production (i.e., an emissions' generator). If the government wasn't devoting any resources towards pollution abatement,  $py_t$  would be the total flow of emissions. But there is abatement ( $f(g_t)$ ,  $f'(g_t) > 0$ ,  $f''(g_t) > 0$ ), which will result to the reduction of total emissions. If we substitute the production function (Eq. (1.7)) in Eq. (1.12), total emissions are:

$$P_t = \frac{pAh_t}{1 + f(g_t)} \quad (1.13)$$

Using Eqs. (1.11) and (1.13), the dynamics of pollution are given by:

$$\mu_{t+1} = \eta\mu_t + \frac{pAh_t}{1 + f(g_t)} = M(\mu_t, h_t) \quad (1.14)$$

### 1.3 Equilibrium

The dynamic equilibrium is characterized by the laws of motion of human capital (Eq. (1.6)) and of pollution (Eq. (1.14)). In order to obtain analytical solutions, we employ the following functional forms:

$$\Gamma(\mu_t) = \gamma + \mu_t \quad (1.15)$$

where  $0 < \gamma < \phi\beta$ .

$$f(g_t) = g_t^2 \quad (1.16)$$

After substituting  $\Gamma(\mu_t)$  and  $f(g_t)$  in Eqs. (1.6) and (1.14) respectively, the evolution of the economy is described by the following system of two first order difference equations of two stock variables (pollution stock ( $\mu_t$ ) and human capital

stock ( $h_t$ ):

$$\mu_{t+1} = \eta\mu_t + \frac{pAh_t}{1 + (TAh_t)^2} \quad (1.17)$$

$$h_{t+1} = \frac{\phi\beta h_t}{\gamma + \mu_t} \quad (1.18)$$

## 1.4 Steady state analysis and dynamics

A steady state is a pair ( $\hat{\mu} \geq 0, \hat{h} \geq 0$ ) such that  $\mu_{t+1} = \mu_t = \hat{\mu}$  and  $h_{t+1} = h_t = \hat{h}$ . Applying the steady state condition in Eqs. (1.17) and (1.18) yields,

$$\Delta\mu_t = 0 \Rightarrow \mu_{t+1} - \mu_t = 0 \Rightarrow \eta\mu_t + \frac{pAh_t}{1 + (TAh_t)^2} - \mu_t = 0 \Rightarrow \hat{\mu} = \frac{pAh_t}{(1 - \eta)(1 + (TAh_t)^2)} \quad (1.19)$$

$$\Delta h_t = 0 \Rightarrow h_{t+1} - h_t = 0 \Rightarrow \frac{\phi\beta h_t}{\gamma + \mu_t} - h_t = 0 \Rightarrow \hat{\mu} = \phi\beta - \gamma \quad (1.20)$$

**Lemma 1** *Assume  $T \in (0, \min[\frac{p}{2(\phi\beta - \gamma)(1 - \eta)}, 1])$ , then there exist two pairs of steady-state equilibria  $(\hat{\mu}, \hat{h}_1)$  and  $(\hat{\mu}, \hat{h}_2)$ , where  $\hat{h}_2 > \hat{h}_1$ . The pair  $(\hat{\mu}, \hat{h}_1)$  is locally stable, while the pair  $(\hat{\mu}, \hat{h}_2)$  is unstable (a saddle).*

**Proof** See Appendix 4.1. □

Now we have all the required information in order to define the long-run equilibrium of the economy. This is done in the following proposition:

**Proposition 1** *Consider  $\mu_0 < \hat{\mu}$  and  $\tilde{h}_0$  such that  $(\mu_0, \tilde{h}_0)$  lies on the saddle path. In the long-run the economy will:*

1. *Converge cyclically to an equilibrium with zero growth and positive pollution, if  $h_0 < \tilde{h}_0$ , or*
2. *Grow at a positive rate, while pollution may evolve along an EKC, if  $h_0 > \tilde{h}_0$ .*

**Proof** It follows from the results in Lemma 1. □

The dynamics of the economy can be illustrated by means of a phase diagram (Figure 1.1), where the  $\Delta h_t = 0$  locus is a horizontal line and the  $\Delta\mu_t = 0$  locus is an inverted U shaped curve, from which we can confirm the implications of Proposition

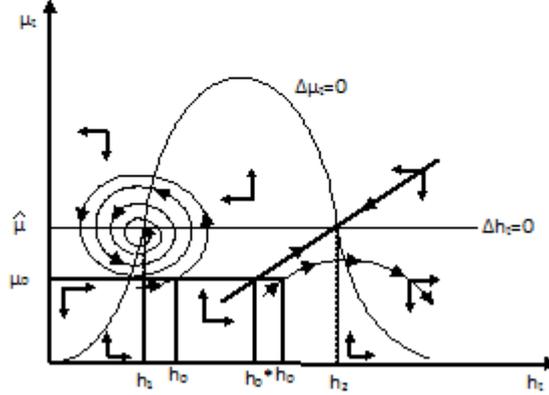


Figure 1.1: Phase diagram for  $h_t$  and  $\mu_t$

1.<sup>2</sup>

Proposition 1 states that when the pair of initial values of pollution and human capital  $(\mu_0, h_0)$  is below the  $\Delta\mu_t = 0$  locus and above the stable path to the saddle point, the economy will converge cyclically to a low income equilibrium. When it is below both the  $\Delta\mu_t = 0$  locus and the saddle path, then there is a higher income economy with an Environmental Kuznets Curve (EKC) and positive growth. The starting conditions with respect to human capital ( $h_0$ ), i.e., whether we have a lower or a higher income economy, determine the long-run prospects of the economy

Why does the economy have cycles? As pollution increases there is a negative health effect which decreases human capital accumulation. From the dynamic equation of pollution (Eq. (1.17)) we notice that, for low values of human capital ( $h_t$ ), pollution ( $\mu_t$ ) is increasing in  $h_t$ , which means that as human capital increases pollution will increase as well. This in turn has negative effects on the human capital of the next period ( $h_{t+1}$ ), and because of the lower human capital, pollution will be lower as well which will have positive effects on the human capital of the subsequent

<sup>2</sup>The actual shape of the  $\Delta\mu_t = 0$  locus might be a bit different from the regular bell-shaped depicted in Figure 1.1, with its maximum being skewed to the left. Even though this might have a quantitative effect on our result, it doesn't change the main point of the analysis qualitatively, i.e., that initial conditions matter.

period ( $h_{t+2}$ ). So, there is a cycle: high level of human capital today, lower level of human capital tomorrow, higher level of human capital the next period and so on.

However, when human capital is above a certain threshold, because we are at a point where pollution is decreasing in  $h_t$ , as human capital increases, pollution might increase at first (to the left of the  $\Delta\mu_t = 0$  locus), but then it will start declining (to the right of the  $\Delta\mu_t = 0$  locus). And this is exactly what an EKC shows: the hypothesized relationship between environmental quality (pollution) and economic development (income). A high level of human capital (income) leads to lower pollution due to abatement and because of lower pollution even higher human capital, but because of higher human capital, even lower pollution due to abatement and so on. So, human capital increases forever, while the pollution stock increases at first followed by a decrease (which is also depicted in the phase diagram).

It is worth mentioning the role of a sufficiently high tax rate in opening the possibility of the virtuous sustained dynamics of human capital and pollution. If the government is to calculate the optimal tax rate then of course the relevant trade-offs should be taken into account. In addition to the beneficial effect of taxation on reducing pollution and therefore on reducing the negative health effect of pollution there is another implication. Taxation will reduce disposable income which will have a negative effect on welfare due to consumption. Thus, in order for the government to find the optimal tax rate they will try to balance off these effects, i.e., the welfare costs and the welfare benefits on pollution. However, finding this optimal tax rate is not an issue of concern for this analysis, but it's an interesting issue for further research. The main point of our analysis is to examine the dynamic implications that arise from environmental taxation.

## 1.5 Conclusion

In this chapter we have built a model in which the dynamics of pollution and human capital accumulation interact and consequently are jointly defined. Although human capital accumulation is considered as one of the main determinants of growth, this is not always the case in our model since the occurrence of pollution is pivotal. When the effect of income (human capital) on pollution is positive and monotonic, the

impact of pollution on health can negatively influence the dynamics of the economy. We have shown that this occurs for lower levels of human capital (or low income economies). After a certain threshold we observe a negative relation between income and pollution, that can be attributed to advanced abatement technologies, environmental awareness etc. of wealthier economies. This is the critical point of our analysis that creates multiple equilibria. The existence of an EKC shows that as income increases pollution will eventually decrease which means that health will be consequently improved. This will reinforce the positive effect of today's income on future income and possibly lead to growth. Given the pollution's effect on human capital accumulation and growth, we have demonstrated that the economy's development path will depend critically on the initial values with respect to human capital.

# Chapter 2

## Crime and pollution

### 2.1 Introduction

The prevalence of violent and criminal behaviour in recent years has become a major concern across the world. Building on the economics of crime literature, the attention of the present paper is mainly focused on how can environmental quality be affected by the detrimental costs of crime on entrepreneurial performance and economic development. Crime has substantial economic consequences both in the short and the long-run. In the short-run, violent and predatory operations destroy part of the physical and human capital stock, imposing direct and indirect costs on businesses, reducing profits and possibly distorting the efficient allocation of funds that could be invested in productive activities. In the long run, as these phenomena enlarge the uncertainty and riskiness of the business environment, domestic and foreign direct investment are discouraged, which, in turn, may impede the accumulation process and reduce the long-run growth rate of the economy.

How are entrepreneurial decisions affected in the presence of crime? Can criminal activity, directly or indirectly, influence a country's overall economic growth? In the process of making employment, production and investment decisions, entrepreneurs are primarily concerned with the so-called investment climate, which refers to the conditions that shape the incentives and opportunities that firms face, like the protection of their property rights, the potential regulatory burdens, the extent of corruption, the quality of infrastructure, etc. According to Investment Climate Surveys carried out by the World Bank (Hallward-Driemeier and Stewart, 2004) with

partners in 53 developing countries, crime ranks sixth over 14 factors which, according to firms, represent an obstacle to the operation and growth of their business. Moreover, considering corruption as a criminal activity as well, crime would climb even higher in the ranking. Papers that evaluate the economic impact of crime from an empirical point of view include Gaviria (2002). Gaviria (2002), drawing on survey data of private firms in Latin America, observes that crime reduces overall economic performance of businesses significantly, and specifically sales growth. Peri (2004) analyses data from 95 Italian provinces during the post World War II period (1951-1991) and finds that the presence of organized crime, as estimated by murder rates, had a significantly negative outcome on regional economic activity. Using employment growth as a measure of economic activity, Peri (2004) shows that there is a negative effect on the annual per capita income growth. Krkoska and Robeck (2006) empirical analysis presents evidence of higher rates of crime in countries with lower FDI inflows - at the state level, as well as a negative link between crime, and job creation and sales growth - at the firm level. Cárdenas and Rozo (2008) provide empirical evidence that crime and violence associated with the illicit drug trade in Colombia resulted in a decline in total factor productivity, which, in turn, decreased annual economic growth by two percentage points after 1980. Daniele and Marani (2008) suggest that there is a strong relationship between criminality and economic deprivation, since these activities tend to discourage both national and inward foreign investment by increasing the risks and costs of doing business. On the same wavelength, Detotto and Otranto (2010) find that crime makes the business environment insecure, increasing uncertainty and reducing trust among agents. Organized crime, in particular, increases the costs and decreases the returns on economic activity acting like a tax on the entire economy. In overall, these circumstances damage economic performance and are translated into reduced investments and lower efficiency. Finally, Enamorado et al. (2014) combine municipality-level data on incomes and crime data for Mexico, and examine the effects of the rapid increase in violent crime on income convergence. Their results indicate a negative impact of drug-related crimes on income growth in Mexican municipalities over the period from 2005 to 2010.

An influential theoretical paper, investigating and analysing the determinants

and impacts of crime, is the seminal work of Becker (1968), in which agents rationally decide whether to become criminals or not, by comparing the anticipated revenues from crime with the revenues from legal activities. Building on Becker (1968), Goglio (2004) supposes that criminal activity can be perceived as a type of economic activity with negative consequences on the long-term competitiveness of local areas or industries, influencing various factors such as human capital, social capital, resource allocation, and entrepreneurship. Shavell (1993) show that the impact of threats - like blackmails, extortion and robbery- are unequivocally to decrease social welfare, which justifies the use of legal measures against them. Konrad and Skaperdas (1998) examine the effects of extortion by gangs, which is the defining activity of organised crime, and explain how extortion can distort the incentives for productive economic activity and can lead to destruction of property. Blackburn et al. (2017) show that the presence of organized crime decreases economic performance by discouraging entrepreneurs from engaging in growth-promoting initiatives, like capital production.

Thus far, we have established, from the aforementioned empirical and theoretical literature, that criminal activity can have negative effects on income/output and growth. Since higher crime is translated to lower income/output and given that income is one of the main generators of pollution, one could presume that, at the outset, higher criminal activity will be associated with lower pollution. Additionally, it is well documented that crime can affect entrepreneurial activities by distorting their investment incentives and decreasing their profits. If the financial cost associated to crime is high, the firm's incentive of adopting advanced technologies is limited, and if this technology adoption is linked with the use of less polluting technologies, then it can negatively affect the environment by increasing pollution (for given level of output). Our analysis aims at examining a model that takes into account both of these effects (the effect of crime on output and on entrepreneurial activity) and trying to realise conditions under which crime increases or decreases pollution. Other papers link organized crime and pollution, like D'Amato and Zoli (2012) who conclude that under certain circumstances, the presence of a mafia type organization operating in the waste cycle and extorting rents which is socially damaging might result to higher production and lower enforcement effort. If the advantages stemming from the rise

in economic activity and enforcement cost savings are substantial, then they can eventually overcome both social costs of the mafia's rent and environmental damages related to illegal disposal. D'Amato et al. (2015) prove the possibility that the presence of organized crime in local governments impedes the realization of a better waste performance.

Specifically, the present paper provides a theoretical framework that permits us to analyse the relation between crime and pollution. In order to do that, we build a three-period overlapping generations model in which the occurrence of crime affects entrepreneurs' economic incentives to invest in pollution abatement technologies. Firms are obliged to pay emission taxes since their production technology is considered polluting. This tax encourages them to undertake environmental investments to secure cleaner technologies which will decrease their financial obligations, but in order to obtain the advanced technology, they need to pay a fixed cost that decreases their profits. The presence of criminal groups that are already extorting money from entrepreneurs (and therefore decreasing their income), reduces the probability of going ahead with the undertaking of the costly anti-polluting investment, which can have implications for aggregate pollution. A key feature of the model is a type of heterogeneity among households, which refers to individuals' different moral values and society's cultural norms, that will affect the intensity of criminal activity and can alter the economy's environmental outcomes. Dependent on initial conditions, multiple equilibria may arise, i.e. an economy with currently low (high) criminality will dynamically be driven to low (high) criminality in the long-run. Namely, we show that current differences in criminal activity, can persist in the long-run due to social norms and, furthermore, can have implications for both total output and pollution. Paradoxically, under certain parameter values, we can have a situation in which a higher crime economy will produce lower output and nevertheless will have higher pollution. In other words, we prove that crime might be one of the explanatory factors for which countries with lower output (less developed) are more polluted. The assertion that environmental quality is poor in low-income economies is well backed up by the data. Figure 2.1 shows air quality (airborne particulate matter concentrations in both rural and urban centres) in developed and developing countries, using data from the World Health Organization (WHO, 2016). Some of

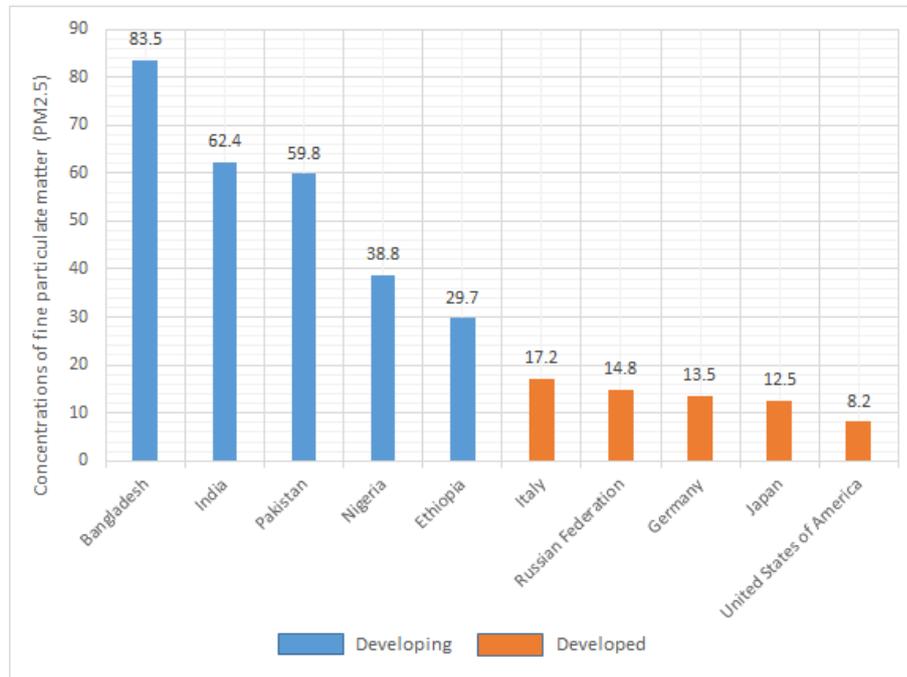


Figure 2.1: Environmental Quality in Developed and Developing Countries

the most populous developed and developing countries are displayed, ranked according to the pollution measure (from most to least polluted), from which it is evident that developing countries are considerably dirtier (higher particulate matter concentrations).

The idea that criminal propensity rests upon individual and cultural characteristics has also drawn the attention of several researchers. Case et al. (1991) find that an individual's tendency to commit a crime rises when his family members and neighbourhood peers are also engaged in criminal activities. Akerlof and Yellen (1993) underline the significant role of social norms -influencing for or against gangs- as additional determinants of the success of organised criminal groups in an area. Glaeser et al. (1996) attempt to explain the high variance of crime rates across time and space and, finally, discover the importance of social interactions in forming tastes and actions, finding positive covariance across agents' decisions about crime. Schrag and Scotchmer (1997) argue that the uneven distribution of crime can be partially elucidated by its self-reinforcing nature, i.e., individuals who reside in high-crime communities will find crime more appealing. Fajnzylber et al. (1998, 2002) observe that crime tends to persist over time (criminal inertia) and provide evidence that violent crime is self-perpetuating. The effect that an agent's choice to become

a criminal is positively related to the incidence of crime of the previous generation which might lead to a dynamic process generating multiple equilibria, has been studied by several theoretical models. In Rasmusen (1996) model, employers make conjectures about potential employees' criminality based on their criminal records and show the possibility of multiple equilibria with different crime rates, focusing on social stigma as a potential source of multiplicity. Schrag and Scotchmer (1997) find that by holding fixed the exogenous factors, with regard to the varied opportunity costs of crime that citizens in different age groups or sub-populations face, there exist multiple equilibria with different crime rates, depending on the criminal justice institutions and the interdependence of citizens' choice problems. Other papers that find multiple equilibria in the presence of crime are Burdett et al. (2003), Roland and Verdier (2003), Huang et al. (2004) and Calvó-Armengol et al. (2007).

A crucial characteristic of our model is the firms' technology choice which is driven by the imposition of an emission tax. Similar to Varvarigos (2014) this tax acts as an incentive for the implementation of cleaner production methods, leading to reduced pollution, which is supported by empirical evidence. Popp (2002) shows that environmental taxes not only lower pollution by shifting behaviour away from polluting activities but also support the development of new production technologies that make pollution abatement less costly in the long-run. In addition, according to an OECD (2007) analysis of the effects of public environmental policy on the inner workings of the firm, environmental taxation favours the introduction of changes in production process measures, likely to reduce environmental impacts at source.

The remaining of this chapter is organised as follows: In Section 2.2, we describe the fundamental characteristics of the economic environment. In Section 2.3, we extend our framework to introduce constant marginal productivity of labour. Section 2.4 concludes.

## 2.2 The Model

We shall employ a 3 period overlapping generations model, where the first period is childhood ( $t$ ) and the next 2 are the periods of adulthood, youth ( $t + 1$ ) and old age ( $t + 2$ ). There are 2 groups of agents separated at birth: households and

entrepreneurs, both of which are of unit mass. All agents are risk neutral and receive utility from consumption when old, i.e.,  $u_{t+1} = c_{t+2}$ .

### 2.2.1 Entrepreneurs

During childhood entrepreneurs are inactive. Their ultimate pursuit is to produce output in the 3rd period of their lives by hiring labour from young workers of the next generation. In a perfectly competitive market where entrepreneurs are price takers and price is normalized to unity, an entrepreneur  $i$  born at time  $t$  will produce when old  $y_{i,t+2}$  units of output according to the following technology:

$$y_{i,t+2} = \frac{l_{i,t+2}^\alpha}{\alpha}$$

where  $l_{t+2}$  is the amount of workers of the same period (born in period  $t + 1$ ) and  $\alpha \in (0, 1)$ . In order to be able to produce this good when they are old, entrepreneurs should choose to undertake a project when they are young. There are 2 alternatives as far as the project they are going to take on is concerned. They can choose a project associated with relatively dirty technology and zero adoption cost or a project associated with relatively clean technology and positive adoption cost. Adopting the relatively dirty technology is costless and effortless, since the entrepreneur need not do anything when he is young. When he is old and by using this type of technology his production will discharge 1 unit of emission per unit of output. By adopting the cleaner technology, the outcome would be  $e$  units of emissions per unit of output, where  $e \in (0, 1)$ . In order to adopt this technology though, the entrepreneur should bear a cost equal to  $k_{t+1}i$ . This cost has 2 components, a component that varies according to the average scale of projects he is going to undertake in the next period,  $k_{t+1} = \bar{k} \frac{\bar{l}_{t+2}^\alpha}{\alpha}$ , (where  $\bar{k} > 0$  and  $\bar{l}_{t+2}$  is the average number of workers of the next period)<sup>1</sup>, and an idiosyncratic component  $i \in (0, 1)$ , where  $i$  is uniformly distributed among entrepreneurs and may be thought of as reflecting individual endowments of technical abilities (skills, knowledge, expertise etc.). Being successful in a project that generates less pollution is determined by each entrepreneur's distinctive abil-

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<sup>1</sup>The general idea behind this assumption is that adoption costs are increasing in the average output of the period that the entrepreneur will produce. To some extent, despite the conceptual relevance, this assumption is just to simplify matters, otherwise the model becomes completely intractable.

ities. To be able to afford the adoption of the cleaner technology when they are young they will borrow  $k_{t+1}i$  from the world financial market. We consider a small open economy, where everyone can borrow and save at the world's fixed interest rate  $r$ . When they are old they should repay  $(1+r)k_{t+1}i$ . The incentive for an entrepreneur to adopt the costly cleaner technology is an emission tax  $\phi \in (0, 1)$ , charged for every unit of emissions.<sup>2</sup> We assume that the government is fully informed about the level of emissions of each entrepreneur. Since the emissions are higher for the relatively dirty production technology, the entrepreneur who adopts this type of technology will have to pay a higher emissions' tax.

An entrepreneur's variable profits,  $\pi_{i,t+2}$ , are given by the following

$$\pi_{i,t+2} = y_{i,t+2} - W_{t+2}l_{i,t+2} - \tilde{\phi}y_{i,t+2} \quad (2.1)$$

where  $\tilde{\phi} = \phi$  if he is using the dirtier technology or  $\tilde{\phi} = \phi e$  if he is using the cleaner technology. Profit maximising firms will offer a wage that is equal to the marginal product of labour times the tax, i.e.,  $W_{t+2} = (1 - \tilde{\phi})l_{i,t+2}^{\alpha-1}$ . In an equilibrium with positive employment for both types of firms (firms that will adopt the cleaner technology are denoted by  $C$  and firms that will adopt the dirtier technology by  $D$ ), the wage paid to workers must be the same, otherwise no worker would work for the firms offering the lower wage. This means that

$$(1 - \phi e)l_{C,t+2}^{\alpha-1} = (1 - \phi)l_{D,t+2}^{\alpha-1} \Rightarrow \frac{l_{C,t+2}}{l_{D,t+2}} = \left(\frac{1 - \phi e}{1 - \phi}\right)^{\frac{1}{1-\alpha}} \quad (2.2)$$

Define  $g = \left(\frac{1 - \phi e}{1 - \phi}\right)^{\frac{1}{1-\alpha}}$  and consider  $l_{C,t+2} = \lambda l_{t+2}$  and  $l_{D,t+2} = (1 - \lambda)l_{t+2}$ , where  $l_{t+2}$  is the number of workers in period  $t + 2$  and  $\lambda \in (0, 1)$  is a composite term to be determined by substituting  $g$ ,  $l_{C,t+2}$  and  $l_{D,t+2}$  in (2.2):

$$\lambda = \frac{g}{1 + g} \quad (2.3)$$

Using  $l_{C,t+2}$ ,  $l_{D,t+2}$  and the production function, the variable profits for the firms that will adopt the cleaner technology are  $\pi_{C,t+2} = (1 - \phi e)(1 - \alpha)\lambda^{\alpha}\frac{l_{t+2}^{\alpha}}{\alpha}$  and for the firms that will adopt the dirtier technology are  $\pi_{D,t+2} = (1 - \phi)(1 - \alpha)(1 - \lambda)^{\alpha}\frac{l_{t+2}^{\alpha}}{\alpha}$ .

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<sup>2</sup>The revenues from the environmental tax are used to finance a stream of government spending which, for simplicity, we assume that it doesn't have a productivity benefit.

In addition to the emission tax, however, when a young entrepreneur is to decide which technology to use and how much to produce, he should take into account another factor that can have an impact on his variable profits. For every entrepreneur there is a probability  $\Pi(\epsilon_t)$  of being visited by a criminal whose only intention is the extortion of money. The probability  $\Pi(\epsilon_t) = \epsilon_t$  is endogenous and it depends on the number of criminals  $\epsilon_t \in (0, 1)$ . The higher the number of criminals, the higher the probability of being visited and extorted by one. Once visited by a criminal, the entrepreneur will lose a fraction  $x$  of his variable profits. The entrepreneur's expected profits given the probability of being extorted by a criminal, are either  $V_{D,t+2} = (1 - \phi)(1 - \alpha)(1 - \lambda)^\alpha \frac{i_{t+2}^\alpha}{\alpha} (1 - \Pi(\epsilon_{t+2})x)$ , if he adopts the dirtier technology or  $V_{C,t+2} = (1 - \phi e)(1 - \alpha)\lambda^\alpha \frac{i_{t+2}^\alpha}{\alpha} (1 - \Pi(\epsilon_{t+2})x) - (1 + r)\bar{k} \frac{i_{t+2}^\alpha}{\alpha}$ , if he adopts the cleaner technology. Naturally, an entrepreneur will decide to adopt the cleaner technology as long as the expected profits from doing so exceeds the profits that he will enjoy if he adopts the dirtier one. The marginal entrepreneur is the one who is indifferent between the two options, i.e., the entrepreneur for whom  $V_{D,t+2} = V_{C,t+2}$ . This expression defines a critical value

$$i_{t+2}^* = \frac{(1 - \alpha)(1 - \Pi(\epsilon_{t+2})x)\Delta}{(1 + r)\bar{k}} \quad (2.4)$$

where  $\Delta = (1 - \phi e)\lambda^\alpha - (1 - \phi)(1 - \lambda)^\alpha$  or  $\Delta = \frac{(1 - \phi e)^{\frac{1}{1-\alpha}} - (1 - \phi)^{\frac{1}{1-\alpha}}}{((1 - \phi e)^{\frac{1}{1-\alpha}} + (1 - \phi)^{\frac{1}{1-\alpha}})^\alpha}$ , so that entrepreneurs for whom  $i < i_t^*$  will choose the clean technology, whereas entrepreneurs for whom  $i > i_t^*$  will choose the dirty technology. Since  $i$  is uniformly distributed on  $[0, 1]$ , we have  $\int_0^{i_t^*} di = i_t^*$ , which is the mass of entrepreneurs who use the clean technology and  $\int_{i_t^*}^1 di = 1 - i_t^*$ , which is the mass of entrepreneurs who use the dirty technology. This critical threshold should be between 0 and 1, since entrepreneurs are of unit mass. It is indeed greater than 0 since it is a collection of positive parameters. A sufficient condition for  $i_t^*$  to be lower than 1 is that  $\bar{k} > \frac{1 - \alpha}{(1 + r)}$ , which is a parameter restriction that is henceforth assumed to hold.

Given the total number of entrepreneurs who will ultimately employ the relatively cleaner technology  $i_t^*$ , it is straightforward to demonstrate the result that is formally presented in

**Proposition 2** *The number of entrepreneurs who will adopt the cleaner technology*

increases when:

1. the emission tax rate  $\phi$  increases;
2. the emission rate  $e$  decreases;
3. the probability of being extorted by criminals, i.e.,  $\Pi(\epsilon)$ , decreases;
4. the world's interest rate  $r$  decreases;
5. the fraction  $x$  of their profits that is being stolen by criminals decreases.

**Proof** Using (2.4), it is straightforward to show that,

$$\frac{\partial i_t^*}{\partial \phi} = \frac{(1-\alpha)(1-\Pi(\epsilon_t)x)}{(1+r)\bar{k}} \left[ \left( \frac{1}{1-\alpha} \right) A + \left( \frac{\alpha}{1-\alpha} \right) \Delta B \right] > 0$$

$$\text{where } A = \frac{((1-\phi)^{\frac{1}{1-\alpha}} - e(1-\phi e)^{\frac{1}{1-\alpha}})}{((1-\phi e)^{\frac{1}{1-\alpha}} + (1-\phi)^{\frac{1}{1-\alpha}})^\alpha} \text{ and } B = \frac{((1-\phi)^{\frac{1}{1-\alpha}} + e(1-\phi e)^{\frac{1}{1-\alpha}})}{((1-\phi e)^{\frac{1}{1-\alpha}} + (1-\phi)^{\frac{1}{1-\alpha}})}$$

$$\frac{\partial i_t^*}{\partial e} = -\frac{(1-\alpha)(1-\Pi(\epsilon_t)x)}{(1+r)\bar{k}} \left[ \frac{\left( \frac{\phi}{1-\alpha} \right) (1-\phi e)^{\frac{\alpha}{1-\alpha}}}{((1-\phi e)^{\frac{1}{1-\alpha}} + (1-\phi)^{\frac{1}{1-\alpha}})^\alpha} \right] [1-\alpha C] < 0$$

$$\text{where } C = \frac{((1-\phi e)^{\frac{1}{1-\alpha}} - (1-\phi)^{\frac{1}{1-\alpha}})}{((1-\phi e)^{\frac{1}{1-\alpha}} + (1-\phi)^{\frac{1}{1-\alpha}})}$$

$$\frac{\partial i_t^*}{\partial \Pi(\epsilon)} = -\frac{x(1-\alpha)}{\bar{k}(1+r)} \Delta < 0$$

$$\frac{\partial i_t^*}{\partial r} = -\frac{(1-\alpha)(1-\Pi(\epsilon_t)x)}{\bar{k}(1+r)} \Delta < 0$$

$$\frac{\partial i_t^*}{\partial x} = -\frac{(1-\alpha)\Pi(\epsilon_t)}{\bar{k}(1+r)} < 0$$

□

The mechanisms behind this outcomes are pretty straightforward. Other things being equal, the higher the emission tax rate ( $\phi$ ) the higher the incentive for an entrepreneur to adopt the relatively cleaner technology, which implies a higher critical value ( $i_t^*$ ). A higher emission rate ( $e$ ) signifies that the difference between the cleaner and the dirtier technology wanes, which means that the benefit in terms of reduced tax is not that significant, so a smaller amount of entrepreneurs will choose the cleaner technology. If an entrepreneur anticipates that there is a higher probability

in the future of being extorted by criminals, he will be disincentivized to choose the cleaner technology, which means a lower critical value ( $i_t^*$ ). This outcome can be explained by the fact that the marginal damage of criminal activity is higher when variable after-tax profits are higher as well (i.e., when the effective tax on emissions is lower due to the adoption of a cleaner technology). Finally, the interest rate ( $r$ ) increases the expected cost of adopting the cleaner technology, whereas an increase in the fraction ( $x$ ) of the entrepreneurial profits that is being purloined by criminals decreases the expected variable profits - both effects induce fewer entrepreneurs to choose the cleaner over the dirtier technology.

### 2.2.2 Households

An individual ( $j$ ), belonging to the group of households, who is born in period  $t$ , is active only during the two periods of his adulthood. When the individual is young he needs to decide whether he will become a worker and supply labour to firms that produce the economy's final good - earning labour income ( $W_{t+1}$ ) or he will become a criminal extorting money from entrepreneurs - earning a percentage ( $x$ ) of their variable profits - and facing the possibility of getting caught and lose all his loot. Individuals save their income so that during the 3rd period of their lives, when they retire, they can fund their consumption spending by using the returns on their savings.

The wage of an individual who becomes a worker is <sup>3</sup>

$$W_{t+1} = (1 - \phi e)l_{C,t+1}^{\alpha-1} = (1 - \phi e)\lambda^{\alpha-1}l_{t+1}^{\alpha-1} \quad (2.5)$$

From  $g = (\frac{1-\phi e}{1-\phi})^{\frac{1}{1-\alpha}}$ , (2.3), and (2.5), we have

$$W_{t+1} = [(1 - \phi)^{\frac{1}{1-\alpha}} + (1 - \phi e)^{\frac{1}{1-\alpha}}]^{1-\alpha} l_{t+1}^{\alpha-1} \quad (2.6)$$

Workers deposit their entire income ( $W_{t+1}$ ) to financial intermediaries and when they are old they will afford consumption expenditures equal to  $(1 + r)W_{t+1}$ . Using

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<sup>3</sup>We could assume that there is a system of law enforcement and that each police official is paid a salary which is financed by a lump-sum tax on workers, but this will make our analysis too complicated without adding anything substantial.

(2.6), the expected utility of a worker is given by

$$E(u_{t+1}^w) = (1+r)W_{t+1} = (1+r)[(1-\phi)^{\frac{1}{1-\alpha}} + (1-\phi e)^{\frac{1}{1-\alpha}}]^{1-\alpha} l_{t+1}^{\alpha-1} \quad (2.7)$$

Consider an individual who is representative of the ones who join a criminal group. The criminal group extorts collectively a payment of  $\bar{X}$  from each firm, which is a fraction of the entrepreneur's variable profits, by intimidating him with the threat of violence should he refuse to abide. We assume that it is prohibitively costly, in terms of personal damage, to the entrepreneurs not to agree to give part of their variable profits.<sup>4</sup> With probability  $i_{t+1}^*$  ( $1 - i_{t+1}^*$ ) they will extort money from an entrepreneur who uses the clean (dirty) technology, so the extortion payment from each firm is  $\bar{X}_{t+1} = x[i_{t+1}^* \pi_{C,t+1} + (1 - i_{t+1}^*) \pi_{D,t+1}]$ . Subsequently, the extorted money are evenly divided to the members of the group, so each criminal is entitled to a share equal to the expected revenues for the group divided by the number of criminals of the group,  $\frac{\bar{X}\Pi(\epsilon_t)}{\epsilon_t} = \frac{\bar{X}\epsilon_t}{\epsilon_t} = \bar{X}$ . Therefore, the representative criminal's revenues are  $\bar{X}_{t+1} = x[i_{t+1}^*(1-\phi e)(1-\alpha)\lambda^\alpha \frac{l_{t+1}^\alpha}{\alpha} + (1-i_{t+1}^*)(1-\phi)(1-\alpha)(1-\lambda)^\alpha \frac{l_{t+1}^\alpha}{\alpha}] = x(1-\alpha) \frac{l_{t+1}^\alpha}{\alpha} [i_{t+1}^*((1-\phi e)\lambda^\alpha - (1-\phi)(1-\lambda)^\alpha) + (1-\phi)(1-\lambda)^\alpha]$ . When criminals are young, they need to save their income so that they can finance their consumption when old and in order to avoid alerting the authorities on their crime and to conceal their illegitimate earnings, they access an underground storage technology, the return to which is lower than the one of the formal financial sector ( $\zeta r$ , where  $\zeta \in (0, 1)$ ). To be more precise, every unit of income they deposit on this storage technology will yield  $1 + \zeta r$  in period  $t + 2$ . We assume that an individual who will choose to become a criminal faces a probability  $q \in (0, 1)$  of being arrested ( $1 - q$  being the probability of evading arrest) and that in the event of being apprehended he incurs a punishment (pecuniary), which includes the seizure of all of his illicit profits.

Agents will choose to behave illegally or not, according to their preferences with regard to both their expected revenues and their moral code. Crime generates a psychological cost incurred irrespective of whether the criminal activity is detected by the authorities or anybody else. For example, committing a crime may induce anxiety, guilt or even loss of self-respect to the individual and this can be interpreted

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<sup>4</sup>We could assume, like Blackburn et al. (2017), that some entrepreneurs may refuse to give in, in which case they would incur severe losses, but such an extension would only add considerable technical complication without changing the main message of the analysis.

as a moral cost for him. This moral cost is captured by a proportional loss of utility and we assume that individuals suffer a cost if their criminal behaviour diverges from the level they perceive to be the social norm. Specifically, for an agent grown up in a society where the crime rate is low and criminal activity is less acceptable, it is more likely his guilt cost to be higher which will disincentivize him to commit a crime and conversely. If  $\epsilon_t$  is the number of criminals in the previous period, then the moral cost experienced by criminals is  $f(\epsilon_t) \in (0, 1)$ , where  $f'(\epsilon_t) > 0$ . For analytical simplicity, we adopt the following functional form,  $f(\epsilon_t) = \gamma\epsilon_t$  ( $\gamma \in (0, 1)$ ). Taking into consideration this moral cost the criminal's expected utility is

$$E(u_{t+1}^c) = (1-q)\gamma\epsilon_t(1+\zeta r)x(1-\alpha)\frac{l_{t+1}^\alpha}{\alpha}[i_{t+1}^*((1-\phi e)\lambda^\alpha - (1-\phi)(1-\lambda)^\alpha) + (1-\phi)(1-\lambda)^\alpha] \quad (2.8)$$

From the preceding analysis,  $(1-\phi e)\lambda^\alpha - (1-\phi)(1-\lambda)^\alpha = \Delta = \frac{(1-\phi e)^{\frac{1}{1-\alpha}} - (1-\phi)^{\frac{1}{1-\alpha}}}{((1-\phi e)^{\frac{1}{1-\alpha}} + (1-\phi)^{\frac{1}{1-\alpha}})^\alpha}$  and  $(1-\phi)(1-\lambda)^\alpha = \frac{(1-\phi)^{\frac{1}{1-\alpha}}}{((1-\phi e)^{\frac{1}{1-\alpha}} + (1-\phi)^{\frac{1}{1-\alpha}})^\alpha}$ .

Now, we define

$$(1-\phi e)^{\frac{1}{1-\alpha}} - (1-\phi)^{\frac{1}{1-\alpha}} = \Omega \quad (2.9)$$

$$(1-\phi e)^{\frac{1}{1-\alpha}} + (1-\phi)^{\frac{1}{1-\alpha}} = \Psi \quad (2.10)$$

Then, from (2.4), (2.8), (2.9) and (2.10), the expected utility of a criminal is

$$E(u_{t+1}^c) = (1-q)\gamma\epsilon_t(1+\zeta r)x(1-\alpha)\frac{l_{t+1}^\alpha}{\alpha}\left[\frac{(1-\alpha)(1-\epsilon_{t+1}x)}{(1+r)\bar{k}}\left(\frac{\Omega}{\Psi^\alpha}\right)^2 + \frac{(1-\phi)^{\frac{1}{1-\alpha}}}{\Psi^\alpha}\right] \quad (2.11)$$

The equilibrium number of criminals will be determined after equating the expected utility of a worker (2.7) and the expected utility of a criminal (2.11). That is,

$$\epsilon_t = \frac{(1+r)^2\bar{k}\Psi\alpha}{(1-q)(1+\zeta r)x\gamma(1-\alpha)[(1-\alpha)\Omega^2(1-\epsilon_{t+1}x) + (1+r)\bar{k}(1-\phi)^{\frac{1}{1-\alpha}}]l_{t+1}} \quad (2.12)$$

It is  $l_{t+1} = 1 - \epsilon_{t+1}$ . Therefore,

$$\epsilon_t = \frac{(1+r)^2\bar{k}\Psi\alpha}{(1-q)\gamma(1+\zeta r)x(1-\alpha)[(1-\alpha)\Omega^2(1-\epsilon_{t+1}x) + (1+r)\bar{k}(1-\phi)^{\frac{1}{1-\alpha}}](1-\epsilon_{t+1})} = g(\epsilon_{t+1}) \quad (2.13)$$

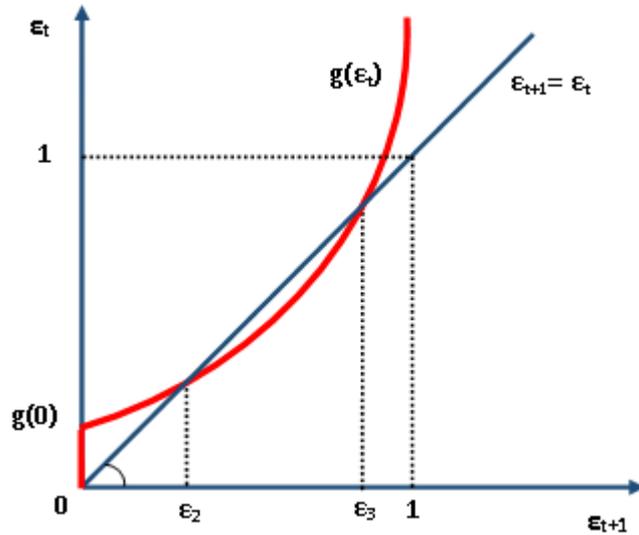


Figure 2.2: Phase diagram for  $\epsilon_{t+1}$  and  $\epsilon_t$

The dynamic equation  $\epsilon_t = g(\epsilon_{t+1})$ ,<sup>5</sup> where  $g' > 0$ ,  $g'' > 0$ , shows that the number of criminals of the next period ( $\epsilon_{t+1}$ ) is positively related to the number of criminals of the current one ( $\epsilon_t$ ), i.e. it shows the evolution of incidence of crime. Why is there a positive relation between  $\epsilon_t$  and  $\epsilon_{t+1}$ ? An increase in the number of criminals of the current period ( $\epsilon_t$ ) will decrease the individuals' moral cost, which means a higher expected utility of being a criminal. But this will distort the equilibrium, since the expected utility of a worker falls short of the expected utility of a criminal. There are 3 ways for the equilibrium to be restored: the expected utility of a criminal to fall, the expected utility of a worker to increase or both. An increase in the number of criminals of the next period ( $\epsilon_{t+1}$ ) has 2 effects and both work towards the restoration of the equilibrium. On one hand, a higher  $\epsilon_{t+1}$  decreases the number of entrepreneurs who use the cleaner technology, which minimizes the expected loot and furthermore the expected utility of a criminal. On the other hand, labour ( $l_{t+1}$ ) falls, which means a higher wage per unit of labour (since wage is a decreasing function of  $l_{t+1}$ ), that leads to a higher expected utility of being a worker. Therefore, an increased number of criminals in the current period (higher  $\epsilon_t$ ) results in an increased number of criminals in the next one (higher  $\epsilon_{t+1}$ ).

<sup>5</sup>Since it is a dynamic equation it is pretty straightforward to infer that it is the number of criminals of the current period ( $\epsilon_t$ ) that affects the number of criminals of the next one ( $\epsilon_{t+1}$ ) and not the other way around.

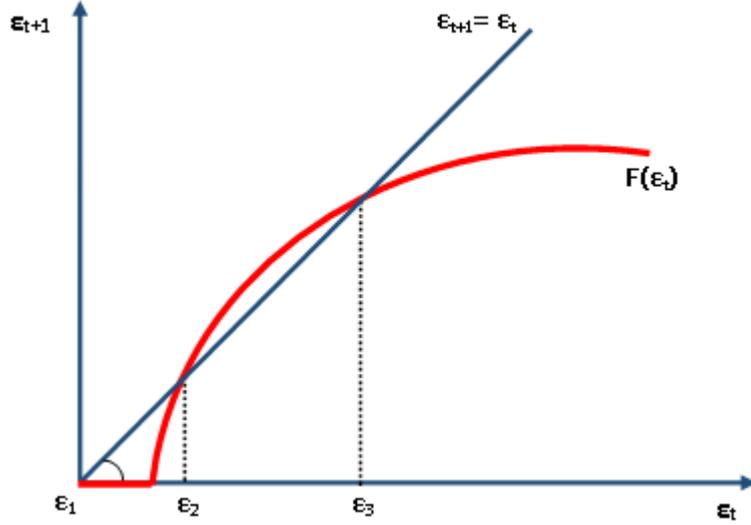


Figure 2.3: Phase diagram for  $\epsilon_t$  and  $\epsilon_{t+1}$

### 2.2.3 The dynamic equilibrium

Let us investigate now whether there are steady state solutions  $\epsilon_{t+1} = \epsilon_t = \epsilon$  to which the incidence of crime will converge in the long-run.

**Lemma 2** *Assuming that  $g(0) > 0$ ,  $g(1) \rightarrow \infty$  and that at least one  $\hat{\epsilon} \in [0, 1]$  such that  $\hat{\epsilon} < g(\hat{\epsilon})$ , then there are two interior steady state equilibria (figure 2.2).*

Reversing figure 2.2 and taking the mirror image we get figure 2.3.

**Proposition 3** *The long-run equilibrium of the economy depends on its initial conditions with respect to the number of criminals ( $\epsilon_0$ ). In particular, for any  $\epsilon_0 > 0$ , the economy will eventually converge:*

1. *To the equilibrium characterised by  $\epsilon_1 = 0$ , if  $\epsilon_0 < \epsilon_2$ , or*
2. *To the equilibrium characterised by  $\epsilon_3$ , if  $\epsilon_0 > \epsilon_2$ .*

**Proof** It follows from the results in Lemma 2. □

The result in Proposition 3 is indicative of a situation where the dynamics of criminal activity generate multiple steady state equilibria, like the one illustrated on the phase diagram of Figure 2.3. Around  $\epsilon_2$ , which is a threshold, future generations will be very reactive to the effects of the current incidence of crime on the moral cost that is captured by  $f(\epsilon_t)$ . If an economy's pre-existing conditions with regard to the number of criminals ( $\epsilon_0$ ) is below the threshold ( $\epsilon_2$ ), then the moral cost

associated with a proportional loss of utility is powerful enough to inspire a higher degree of law compliance, thus decreasing the incidence of crime at a higher rate over time. Therefore, the number of criminals gradually declines, until it converges to the stable equilibrium  $\epsilon_1$ , that corresponds to zero criminal activity. If the economy's prior conditions ( $\epsilon_0$ ) is above the threshold, the moral cost is not sufficient enough to deter many agents from committing illegal acts, which suggests that the incidence of crime is intensified over time, until it converges to the stable equilibrium  $\epsilon_3$ , indicating a state with high criminal activity. From the preceding discussion we can infer that the incidence of crime is persistent, i.e., low (high) criminal activity today will imply low (high) criminal activity tomorrow and so on.

Thus far our analysis has focused on the determinants of criminal activity and its persistence. Let us investigate now the procedure through which crime can affect environmental quality. There are two routes in this procedure, the first one is related to the entrepreneurial technology choice and the second one to the household's choice of joining or not the labour force. At the outset, crime can have two conflicting effects on the environment. On the one hand, because of the fixed cost of investing in the clean technology, since criminals take away a fraction of the entrepreneur's income, the higher the number of criminals, the higher the probability of being visited by a criminal, so the lower the number of firms willing to adopt the cleaner technology, and consequently, the higher the emission rate. So, for given output the higher the pollution. On the other hand, the higher the number of criminals, the lower the supply of labour (since individuals who are criminals cannot be workers), which means the lower the total output. So, for given emission rate, the lower the pollution.

## 2.3 Extension

For analytical purposes we now use a model in which for simplicity we will assume that workers are allocated randomly to firms and there is no labour mobility. Additional simplifying assumptions are that the adoption cost of the cleaner technology becomes fixed ( $ki$ ) and that workers face own moral cost ( $j$ ).

### 2.3.1 Entrepreneurs

Entrepreneurs produce output in the 3rd period of their lives ( $t + 2$ ), either by using solely their own effort, in which case total output is  $\underline{a}$  or by combining their personal effort with labour from young workers of the next generation ( $l_{t+2}$ ), in which case they produce  $\bar{a} + wl_{t+2}$ . An entrepreneur born at time  $t$  will produce when old a single variety of a homogeneous good (there is perfect competition where entrepreneurs are price takers and price is normalized to 1) according to the following technology:

$$y_{t+2} = \begin{cases} \underline{a} \\ \bar{a} + wl_{t+2} \end{cases}$$

where  $\bar{a} > \underline{a}$ . Even if an entrepreneur's contribution is separable from the worker's contribution, entrepreneurs will always have an incentive (optimally) to hire workers since their profits would be higher. This can be interpreted as a complementarity, as the occurrence of workers improves the entrepreneur's productivity. So, an old entrepreneur will produce  $y_{t+2} = \bar{a} + wl_{t+2}$ , by hiring a number of workers ( $l_{t+2}$ ) when the wage per unit of labour is  $W_{t+2}$ .

In order to adopt the cleaner technology, the entrepreneur should bear a cost (a type of fixed cost) equal to  $ki$ . This cost has 2 components, a fixed component  $k > 0$  and the idiosyncratic component  $i \in (0, 1)$ . To be able to afford the adoption of the cleaner technology they will borrow  $ki$  from the world financial market and when they are old they should repay  $(1 + r)ki$ . There is an emission tax  $\varphi \in (0, 1)$ , charged for every unit of emissions.

An entrepreneur's variable profits,  $\pi$ , are given by the following

$$\pi_{t+2} = y_{t+2} - W_{t+2}l_{t+2} - \tilde{\phi}y_{t+2} \quad (2.14)$$

and the wage is  $W_{t+2} = (1 - \tilde{\phi})w$ . Substituting this in (2.14) and using the production function, yields

$$\pi_{t+2} = \bar{a}(1 - \tilde{\phi}) = \bar{\pi}, \forall t \quad (2.15)$$

i.e., in equilibrium is constant.

The entrepreneur's expected variable profits given the probability of being extorted by a criminal, are either  $V_D = \bar{a}(1 - \phi)(1 - \Pi(\epsilon_t)x)$ , if he adopts the dirtier

technology or  $V_C = \bar{a}(1 - \phi e)(1 - \Pi(\epsilon_t)x) - (1 + r)ki$ , if he adopts the cleaner technology. Naturally, an entrepreneur will decide to adopt the cleaner technology as long as the expected variable profits from doing so exceeds the profits that he will enjoy if he adopts the dirtier one. The marginal entrepreneur is the one for whom  $V_D = V_C$ , or

$$i_t^* = \frac{\bar{a}\phi(1 - \Pi(\epsilon_t)x)(1 - e)}{k(1 + r)} \quad (2.16)$$

so that entrepreneurs for whom  $i < i_t^*$  will choose the clean technology, whereas entrepreneurs for whom  $i > i_t^*$  will choose the dirty technology. This critical threshold should be between 0 and 1, since entrepreneurs are of unit mass. It is indeed greater than 0 since it is a collection of positive parameters. A sufficient condition for  $i_t^*$  to be lower than 1 is that  $k > \frac{\bar{a}\phi(1-e)}{(1+r)}$ , which is a parameter restriction that is henceforth assumed to hold.

Given the total number of entrepreneurs who will ultimately employ the relatively cleaner technology  $i_t^*$ , it is straightforward to demonstrate the result that is formally presented in

**Proposition 4** *The number of entrepreneurs who will adopt the cleaner technology increases when:*

1. *the emission tax rate  $\phi$  increases;*
2. *the emission rate  $e$  decreases;*
3. *the probability of being extorted by criminals, i.e.,  $\Pi(\epsilon)$ , decreases;*
4. *the world's interest rate  $r$  decreases;*
5. *the fraction  $x$  of their profits that is being stolen by criminals decreases.*

**Proof** Using (2.3), it is straightforward to show that,

$$\frac{\partial i_t^*}{\partial \phi} = \frac{\bar{a}(1 - \Pi(\epsilon_t)x)(1 - e)}{k(1 + r)} > 0$$

$$\frac{\partial i_t^*}{\partial e} = -\frac{\bar{a}\phi(1 - \Pi(\epsilon_t)x)}{k(1 + r)} < 0$$

$$\frac{\partial i_t^*}{\partial \Pi(\epsilon)} = -\frac{\bar{a}\phi x(1 - e)}{k(1 + r)} < 0$$

$$\frac{\partial i_t^*}{\partial r} = \frac{\bar{a}\phi k(1 - \Pi(\epsilon_t)x)(1 - e)}{(k(1 + r))^2} < 0$$

$$\frac{\partial i_t^*}{\partial x} = -\frac{\bar{a}\phi\Pi(\epsilon_t)(1 - e)}{k(1 + r)} < 0$$

□

The mechanisms behind this outcomes are the same with the ones of the previous model.

### 2.3.2 Households

When the individual ( $j$ ) is young he needs to decide whether he will become a worker or he will become a criminal. The individual who becomes a worker, when calculating his expected wage, will take into account both the probability of being hired by a firm that uses the cleaner technology and the probability of being hired by a firm that uses the dirtier one because his wage is a function of the emission tax the firm pays. If he is employed by a firm that uses the cleaner (dirtier) technology his wage will be higher (lower) since the corresponding emission tax would be lower (higher). The probability of being hired by a firm that uses the cleaner technology is equal to the mass of firms that use this type of technology, i.e.  $i_t^*$  and  $(1 - i_t^*)$  is the probability of being hired by a firm that uses the dirtier technology. If  $W_c = (1 - \phi e)w$  is the offered wage of each firm that uses the cleaner technology and  $W_d = (1 - \phi)w$  is the offered wage of each firm that uses the dirtier technology, the worker's expected wage would be

$$W_t = i_t^*(1 - \phi e)w + (1 - i_t^*)(1 - \phi)w = w(1 - \phi(1 - i_t^*(1 - e))) \quad (2.17)$$

The expected utility of a worker is given by

$$E(u_w) = (1 + r)W_t = (1 + r)w(1 - \phi(1 - i_t^*(1 - e))) \quad (2.18)$$

Consider an individual who is representative of the ones who join a criminal group. From (2.15), the representative criminal's revenues are  $\bar{X}_t = x\bar{\pi} = x(i_t^*\bar{a}(1 -$

$$\phi e) + (1 - i_t^*)\bar{a}(1 - \phi)) = \bar{a}x(1 - \phi(1 - i_t^*(1 - e))).$$

Agents will choose to behave illegally or not, according to their preferences with regard to both their expected revenues and their moral code. The moral cost is captured by a proportional loss of utility and composed of two different components, an idiosyncratic component and a social norm. As far as the first component is concerned, and as a means of introducing the characteristics that will drive some individuals to become criminals, we assume that individuals are heterogeneous in their moral values. As for the second component, we assume (as in the preceding model) that individuals suffer a cost if their criminal behaviour diverges from the level they perceive to be the social norm. If  $j$  ( $j \in (0, 1)$ ) is the variable which differentiates households according to their moral concerns and  $\epsilon_t$  is the number of criminals in the previous period, then the moral cost experienced by criminals is  $f(j, \epsilon_t)$ , where  $f_j > 0$  and  $f_{\epsilon_t} < 0$ . For analytical simplicity, we adopt the following functional form,  $f(j, \epsilon_t) = 1 - (1 - j)\epsilon_t$ .<sup>6</sup> Taking into consideration this moral cost the criminal's expected utility is

$$E(u_c) = (1 - q)(1 + \zeta r)\bar{a}x(1 - \phi(1 - i_t^*(1 - e)))(1 - j)\epsilon_t \quad (2.19)$$

When an individual is to decide whether to become a worker or a criminal, he will compare his expected utilities  $E(u_w)$  and  $E(u_c)$ .

**Lemma 3** *There exists a critical value  $j^*$ , such that, all types  $j < j^*$  will choose to become criminals whereas all types  $j \geq j^*$  will choose to become workers.*

**Proof** For someone to become a criminal  $E(u_w) \leq E(u_c)$  or  $1 - j \geq \frac{(1+r)w}{(1+\zeta r)\bar{a}x(1-q)\epsilon_t}$ . Let's assume that  $(1 + r)w < (1 + \zeta r)\bar{a}x(1 - q)$  and define  $\frac{(1+r)w}{(1+\zeta r)\bar{a}x(1-q)} = \theta$ , so someone will become a criminal when  $1 - j \geq \frac{\theta}{\epsilon_t}$  or  $j \leq 1 - \frac{\theta}{\epsilon_t}$ . The critical agent who is indifferent between the two options is

$$j^* = 1 - \frac{\theta}{\epsilon_t} \quad (2.20)$$

□

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<sup>6</sup>We assume that the exact number of criminals of the previous period is not known to the society, but nevertheless there is a general idea of the extent of criminal activity. A more general functional form for the moral cost would be:  $f(j, \epsilon_t) = 1 - (1 - j)\gamma\epsilon_t$ , where  $\gamma > 0$ . In order to save on notation, we normalize  $\gamma$  to 1, since qualitatively nothing will change.

Based on the critical value of  $j$  ( $j^*$ ) and given that  $j$  is between 0 and 1, the mass of criminals is  $\int_0^{j^*} dj = j^* = \epsilon_{t+1}$ . Combining the mass of criminals and equation (2.20), we have the following dynamic equation

$$\epsilon_{t+1} = \max\left[0, 1 - \frac{\theta}{\epsilon_t}\right] = f(\epsilon_t) \quad (2.21)$$

where  $f' > 0$ , which shows that the number of criminals of the current period ( $\epsilon_{t+1}$ ) is positively related to the number of criminals of the previous one ( $\epsilon_t$ ), i.e. it shows the evolution of incidence of crime. The possibility of a corner solution exists, because when  $\epsilon_t$  is sufficiently low, the moral cost is so high that no-one would want to become a criminal and everyone will behave legally. As criminality increases, the society's norms will be adapted accordingly, which means decreased moral cost of becoming a criminal, hence, a higher share of the population will be impelled to be involved with illicit activities.

### 2.3.3 The dynamic equilibrium

Let us investigate now whether there are steady state solutions  $\epsilon_{t+1} = \epsilon_t = \epsilon$  to which the incidence of crime will converge in the long-run.

**Lemma 4** *There are three steady state equilibria  $\epsilon_1, \epsilon_2$  and  $\epsilon_3$ , where  $\epsilon_1 < \epsilon_2 < \epsilon_3$ . Two of these equilibria,  $\epsilon_1$  and  $\epsilon_3$ , are locally asymptotically stable, whereas  $\epsilon_2$  is unstable.*

**Proof** Using  $\epsilon_{t+1} = \epsilon_t = \epsilon$  in equation (2.8) yields  $\epsilon = 1 - \frac{\theta}{\epsilon}$  or  $\epsilon^2 - \epsilon + \theta = 0$ . The quadratic equation has 2 roots,  $\epsilon_2 = \frac{1 - \sqrt{1 - 4\theta}}{2}$  and  $\epsilon_3 = \frac{1 + \sqrt{1 - 4\theta}}{2}$ . For the 2 roots to be real and distinct, we assume that  $1 - 4\theta > 0$  or  $\theta < \frac{1}{4}$  and using this, it is quite straightforward to establish that  $0 < \epsilon_2 < \epsilon_3 < 1$ . There is another steady state which is derived from the fact that  $\epsilon_{t+1} = \max\left[0, 1 - \frac{\theta}{\epsilon_t}\right]$ . For  $\epsilon_t \leq \theta$ ,  $\epsilon_{t+1} = 0$ , so from  $\epsilon_{t+1} = \epsilon_t$  and given the non-negativity of the variable  $\epsilon_t$ , the third steady state is  $\epsilon_1 = 0$ , which is stable. By evaluating the first derivative of  $f(\epsilon_t)$ , we obtain  $f_{\epsilon_t}(\epsilon_2) > 1$  and  $f_{\epsilon_t}(\epsilon_3) < 1$ , thus verifying that there are 2 stable and one unstable steady states.  $\square$

The result from Lemma 4 facilitates us in finding the economy's dynamic behaviour and transitional dynamics. We can formally demonstrate these ideas in the form of

**Proposition 5** *The long-run equilibrium of the economy depends on its initial conditions with respect to the number of criminals ( $\epsilon_0$ ). In particular, for any  $\epsilon_0 > 0$ , the economy will eventually converge:*

1. *To the equilibrium characterised by  $\epsilon_1 = 0$ , if  $\epsilon_0 < \epsilon_2$ , or*
2. *To the equilibrium characterised by  $\epsilon_3 = \frac{1+\sqrt{1-4\theta}}{2}$ , if  $\epsilon_0 > \epsilon_2$ .*

**Proof** It follows from the results in Lemma 4. □

The analysis of the results in Proposition 5 is similar to the one in Proposition 3.

### 2.3.4 The effect of crime on the environment

As mentioned in section 2.2.3, crime can have two conflicting effects on the environment. On the one hand, because of the fixed cost of investing in the clean technology, the higher the number of criminals, the higher the emission rate. So, for given output the higher the pollution. On the other hand, the higher the number of criminals, the lower the total output. So, for given emission rate, the lower the pollution.

In order to examine which of the two conflicting effects will dominate, we first need to calculate aggregate pollution ( $P$ ). If the aggregate emission rate is  $p$  and total output is  $y$ , then aggregate pollution is

$$P = py \tag{2.22}$$

For the economy with an initial value for  $\epsilon$  lower than the threshold, i.e., when  $\epsilon_0 < \epsilon_2$ , we know that the number of criminals in the steady state is zero, which implies that all individuals are workers ( $l_{t+2} = 1$ ). So, total output is

$$y_1 = \bar{a} + w \tag{2.23}$$

and the emission rate consists of the emissions of both the firms that use the cleaner

technology and the firms that use the dirtier one,

$$p_1 = i_t^* e + (1 - i_t^*) = 1 - i_t^*(1 - e) \quad (2.24)$$

Substituting  $\Pi(\epsilon_t) = \epsilon_t = 0$  in equation (2.16) and combining it with equation (2.24), yields

$$p_1 = 1 - \frac{\bar{a}\phi(1 - e)^2}{k(1 + r)} \quad (2.25)$$

From (2.23) and (2.25), total pollution for the lower steady state is given by

$$P_1 = p_1 y_1 = \left(1 - \frac{\bar{a}\phi(1 - e)^2}{k(1 + r)}\right)(\bar{a} + w) \quad (2.26)$$

If the initial value for the number of criminals is  $\epsilon_0 \geq \epsilon_2$ , then in the steady state  $\epsilon_3 = \frac{1 + \sqrt{1 - 4\theta}}{2}$ , which indicates that the number of workers are  $1 - \epsilon_3$  or  $l_{t+2} = 1 - \frac{1 + \sqrt{1 - 4\theta}}{2} = \frac{1 - \sqrt{1 - 4\theta}}{2}$ . It follows that total output is

$$y_2 = \bar{a} + w l_{t+2} = \bar{a} + \frac{w(1 - \sqrt{1 - 4\theta})}{2} \quad (2.27)$$

For  $\Pi(\epsilon) = \epsilon = \frac{1 + \sqrt{1 - 4\theta}}{2}$  and using (2.16) and (2.24), the emission rate is

$$p_2 = 1 + \frac{\bar{a}\phi(1 - e)^2(x(1 + \sqrt{1 - 4\theta}) - 2)}{2k(1 + r)} \quad (2.28)$$

Combining (2.27) and (2.28) gives us

$$P_2 = p_2 y_2 = \left(1 + \frac{\bar{a}\phi(1 - e)^2(x(1 + \sqrt{1 - 4\theta}) - 2)}{2k(1 + r)}\right)\left(\bar{a} + \frac{w(1 - \sqrt{1 - 4\theta})}{2}\right), \quad (2.29)$$

which is total pollution for the higher steady state.

**Proposition 6** *There exists a critical value,  $\hat{e}$ , for which the economy with higher criminal activity although it produces less output, actually, it has higher pollution.*

**Proof**  $P_2 > P_1$  or  $P_2 - P_1 > 0 \Rightarrow \left(1 + \frac{\bar{a}\phi(1 - e)^2(x(1 + \sqrt{1 - 4\theta}) - 2)}{2k(1 + r)}\right)\left(\bar{a} + \frac{w(1 - \sqrt{1 - 4\theta})}{2}\right) - \left(1 - \frac{\bar{a}\phi(1 - e)^2}{k(1 + r)}\right)(\bar{a} + w) > 0 \Rightarrow \hat{e} \leq 1 - \sqrt{\frac{kw(1 + r)}{\bar{a}\phi(\bar{a}x + w + \frac{1}{2}wx(1 - \sqrt{1 - 4\frac{(1 + r)w}{\bar{a}(1 - q)x(1 + \zeta r))}}))}}$   $\square$

The main implication from Proposition 6 is that, under certain circumstances, the effect that higher criminal activity leads to higher pollution, will dominate.

This means that we can have a situation in which the economy that produces less output (because of the lower number of workers), actually has higher pollution, since the higher number of criminals decreases the number of investments in cleaner technologies and consequently leads to higher emissions' rate intensity.

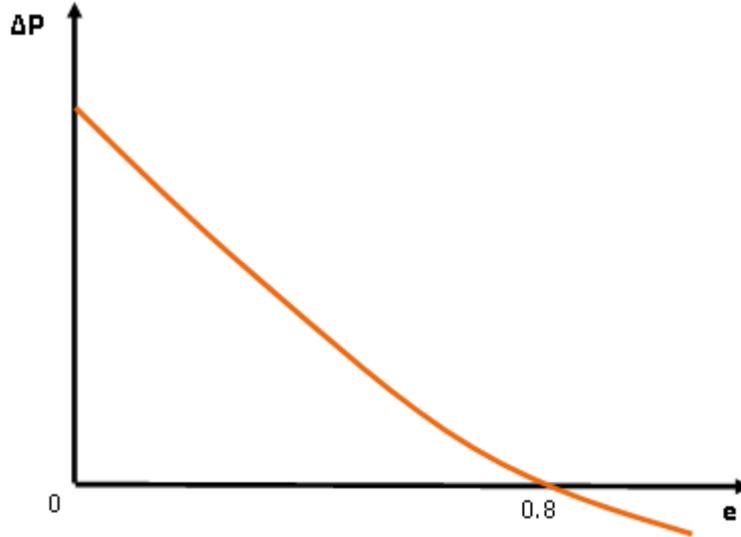


Figure 2.4: A numerical example for  $\Delta P > 0$

For illustrative purposes, Figure 2.4 verifies that there are parameter values for which total pollution can be higher for the high crime economy compared to the low crime economy, even if production is low. In other words, it shows that the difference between  $P_2$  and  $P_1$  ( $\Delta P$ ) is positive. Specifically, it plots this difference ( $\Delta P$ ) against the units of emissions per unit of output ( $e$ ), using  $\bar{a} = 269.354$ ,  $k = 30.4$ ,  $r = 0.157$ ,  $w = 1.4$ ,  $x = 0.128$ ,  $\phi = 0.1488$ ,  $\zeta = 0.491$  and  $q = 0.374$ .

## 2.4 Conclusion

The aim of the present paper was to determine the sources of crime persistence and investigate their implications for an economy's environmental quality. We have built a model in which firms' endogenous technology choice, is simultaneously driven by an environmental tax and the presence of criminal activity. It is shown that the emission rate, the emission tax rate, the probability of extortion and the extorted fraction of the firm's variable profit, are all crucial factors in the determination of the number of entrepreneurs who will adopt the less polluting technology, which

can have an impact on the environment. At the same time, the extent of criminal activity is determined by the households' moral codes which are defined by both their personal attributes and the society's norms. The introduction of an intergenerational externality in the determination of cultural norms and moral values is an underlying source of dynamics which explains the incidence of criminality among individuals. This dynamic process may generate 3 steady state equilibria, one of which is unstable and acts as a threshold. Therefore, crime will converge to a long-run equilibrium where its magnitude can be either low or high, depending on whether the economy's initial conditions regarding the number of criminals lies below or above the threshold. By comparing two economies with the same structural characteristics, apart from the number of criminals, determined by the social norms, there is a chance that these economies will completely diverge. Given the cultural externality's effect on households' decision of pursuing a life of crime or not, which indirectly affects total output, and the criminality's effect on entrepreneurs' incentive for cleaner technologies, there can be a negative outcome on the environment. As we have seen, there exist circumstances under which a high crime economy, that produces less, actually has higher pollution. Our model could be extended by differentiating between cultural norm transmission via the parents or via the wider contemporaneous environment (Bisin and Verdier, 2001).

# Chapter 3

## Minimum Quality Standards under Asymmetric Information

### 3.1 Introduction

In this chapter we will try to address the question of why should quality be regulated and if there is an economic rationale behind it. Many authors have tried to justify the policy intervention regarding the quality of a good, based on the fact that consumers in many cases are not able to accurately ascertain the quality of a good, like for example the quality of a pharmaceutical product or of a product whose process has severe environmental repercussions, and the main issue in such a case is whether there are incentives for firms to supply good quality (Tirole, 1988). Another reason for regulating quality occurs in markets, where firms can loose competition by offering products of different quality to consumers with different willingness to pay for quality. But, it is established that the lessening of competition results in a not Pareto efficient allocation of resources, as prices go up. In that case, a policy maker can interfere, without being too interventionist, by setting a minimum quality standard (MQS), which will narrow the quality disparities and will minimize distortions. As its name suggests, a MQS determines a minimum level of product quality that a firm must provide to its consumers (in order to eschew big fines). A well-drawn MQS can drive the quality that firms provide to consumers of low quality products towards welfare maximizing levels.

The majority of the MQS literature employ models of oligopolistic competition

with pure vertical product differentiation<sup>1</sup>. In these models, a MQS can offset the propensity of firms to provide different levels of product quality in order to lessen the intensity of price competition. By enforcing a MQS that is equal or just exceeds the quality level that the low quality seller would provide in an unregulated market (duopoly), a regulator can impel the firms to supply products with less divergent quality levels. This leads to higher quality levels for both firms and to fiercer price competition that can enhance consumers' surplus and aggregate welfare in situations where higher levels of product quality increase firms' fixed costs of production, but do not change their marginal costs (Ronnen, 1991). However, if marginal costs of production increase as quality level rise, a MQS will not always increase welfare. The higher prices induced by the increased costs related to the MQS may as well decrease welfare (Crampes and Hollander, 1995). Another setting where welfare can be reduced by a MQS imposition, is the one in which firms engage in Cournot competition (competing in quantities), rather than Bertrand competition (competing in prices). In this setting, when the MQS compels the low-quality firm to increase its quality, it also increases its output level. The increased output induces the high quality firm to make cutbacks in its output. A possible consequence is higher product's price, which can cause welfare reduction (Valletti, 2000). A MQS can also decrease welfare in industries with more than two firms (Scarpa, 1998). Welfare effects of a MQS can also differ with the timing of quality and entry choices of the firms and with the sequencing of selection of standards and quality levels (Lutz et al., 2000). Maxwell (1998) observes that a firm's incentive to innovate in order to shrink the costs of supplying quality might be limited when a regulator sets a higher MQS in response to a realized decline in the costs of supplying quality. Ecchia and Lambertini (1997) show that by promoting more contiguous quality levels, a MQS can increase the revenues from defecting from a collusive price agreement, and can thereby restrain the probability of successful collusion. In summary, the outcomes of a MQS are varying and complicated.

Beyond the typical definition of "regulation", namely constraints imposed upon

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<sup>1</sup>In a vertical differentiated product space, all consumers agree over the most preferred mix of characteristics and more generally over the preference ordering. A typical example is quality. Most agree that higher quality is preferable. However, some consumers may still purchase a lower quality good. The consumers' income and the goods' prices determine their ultimate choice. All consumers prefer high quality for a given price (Tirole, 1988).

firms by government, there is a relatively new phenomenon in the field of environmental economics, which has to do with corporate environmental initiatives for self-regulation. “Corporate environmentalism” is a tool for influencing the behaviour of legislators and regulators, by pre-empting mandatory government regulations or for attracting high income consumers who are willing to pay a premium for safer or more environmentally friendly products (Lutz et al., 2000). A more explicit applicability for “corporate environmentalism” is that of the voluntary adoption of cleaner products or processes. Quite a few authors have suggested that “corporate environmentalism” can yield welfare improvements, although they cannot be guaranteed. Arora and Gangopadhyay (1995) develop a model in which firms over-comply with regulations aiming at attracting high income consumers and replicate Ronnen (1991) result that a MQS, if set appropriately, is welfare-improving. Maxwell et al. (2000) consider self-regulation as a means of pre-empting mandatory regulations and even though they assume that the legislature is politically motivated by interest group pressures, they still find self-regulation to be welfare-improving in a standard interest-group setting. On the contrary, Lutz et al. (2000) question the benefits of “corporate environmentalism”. Lutz et al. (2000) study the effects of corporate self-regulation and employ a duopolistic model of vertical product differentiation, in which the 2 firms (high and low quality) compete in both quality and price. The model includes both “green” consumers and a welfare-maximizing regulator who sets environmental standards and show that this setting can be welfare reducing. The main difference between their model and previous ones of MQSs is the timing of firm and government movements. Earlier models have studied how both high and low quality firms act in response to the imposition of the standard, making the assumption that the regulator moves first and firms follow. Lutz et al. (2000) model confers the leadership role to a high quality firm, by allowing the firm to choose its level of environmental consciousness (that is her quality level) prior to the setting of the standard by the regulator. The high quality firm will pre-commit to a quality level (by making a sunk investment in an environmental technology that goes beyond current industry practice but only by a modest amount) that is lower to the level of quality that would have occurred should the regulator had introduced the MQS first. This will induce the regulator to set a lower standard because he

is concerned about the firms' profits that would be probably decreased by a higher MQS and about the lessening of product differentiation that affects consumers' surplus. Hence, both the high and the low quality firm will provide a lower quality level, which means higher profits for them, but at the same time lower consumers' surplus. As a result, social welfare will be lower than if the regulator had introduced the MQS first. The main objective of this chapter is to incorporate asymmetric information to a simplified version of the Lutz et al. (2000) model (using a monopoly instead of a duopoly) and extend it to a signalling model. We shall be using one key characteristic of Lutz et al. (2000) model, in which the firm moves first by choosing its quality level, and the MQS setting by the regulator follows.

The majority of the MQS literature assumes a context of perfect information about quality for consumers, as, for example, in Ronnen (1991), Crampes and Hollander (1995), Ecchia and Lambertini (1997), Scarpa (1998), Lutz et al. (2000), Valletti (2000). Some other papers focus on the standard in a context of imperfect information for consumers, namely that the adoption of a MQS policy is not necessarily related to consumer's ability to observe quality prior to purchase, as in Leland (1979), Shapiro (1983), Garella and Petrakis (2008) and Buehler and Schuett (2014). There are only a few papers in the MQS literature that assume incomplete information for the regulator (Denicolo, 2008), and in particular regarding the firm's operational structure and cost data, which is a more realistic assumption.

Even though, inferior information by the regulator on firms costs has not been extensively studied in the MQS literature, it is a standard assumption of another strand on price regulation. In these models, there is a designated regulator who seeks to control efficiency in a monopolistic market that competition might otherwise offer. If the regulator is perfectly informed about the demand function and cost conditions of the monopolist, his job is relatively straightforward, setting regulation rules such as price equal to marginal cost or average cost, differential pricing, non-linear tariffs etc. (Braeutigam, 1989). However, when the regulator's knowledge is limited regarding the environment in which the firm operates, the optimal regulatory policy practice, differs significantly. In this case, the regulator should establish a pricing rule, with which the firm must comply, without knowing the monopolist's

cost function (i.e., if the firm is of low or high cost).<sup>2</sup> My model is similar, in terms of the asymmetry of information with respect to the cost function between the monopolist and the regulator. The main difference is the use of the firm's quality as a signal, which is the variable that is being regulated.

One of the most relevant articles for my analysis is Denicolo (2008). In an asymmetric duopoly subject to an environmental standard regulation, in which firms have private information on their heterogeneous cost of complying with a stricter regulation (which is one of the assumptions of my model), Denicolo (2008) shows that firms may over-comply in order to signal to the regulator that compliance costs are low. As a consequence, the regulator, in his effort to balance firms' profits, consumer welfare and environmental externalities, will mandate the adoption of a higher level of quality. What motivates the more efficient firm to voluntarily over-comply is to raise its rival's cost by inducing the government to enforce a stricter regulation (or increase the environmental standard). What is different in my paper is that, in equilibrium, efficient firms might choose a (lower) level of quality in order to confuse the regulator and convince him to set a lower MQS.

Despite the fact that MQSs are usually set in order to raise the qualities of goods produced and consumed, this chapter shows that with a MQS, the aggregate quality may actually be lower than it would have been without any regulation. This is quite paradoxical, given the standard rationale for a MQS. The reason for this paradoxical result is that under MQS firms may try to signal that increasing quality is costly, and in order to do that they will set a lower quality. The policy implication of our result is that, under certain circumstances, the regulator may optimally choose to pre-commit not to regulate, as in this case social welfare could be higher than in the scenario where the regulator is free to step in. The simplest possible setting in which our result can be demonstrated is a monopoly model. As is well known, in a monopoly the firm may have incentives to distort the quality. Spence (1975) shows

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<sup>2</sup>In Baron and Myerson (1982), there exists a natural monopolist who is facing regulation by a regulator whose objective is to maximize a linear social welfare function of the consumers' surplus and the firm's profits. A revelation game is designed, that impels the firm to reveal its costs, and then the output price and subsidy are established. Baron and Besanko (1984b) investigate a one-period model of regulatory pricing under asymmetric information where a firm's costs are audited ex post. Baron and Besanko (1984a) analyse a multi-period model in which the regulated firm has private information regarding its costs and a regulatory policy is established for every period.

that the monopolist may either over-provide or under-provide quality, depending on the way quality affects market demand. The general intuition is as follows: what drives the monopolist's choice of the quality level is the marginal effect of quality on demand, i.e. the effect on the marginal buyer. But from a social point the optimal choice must depend on the average effect of increasing quality. Since the impact of quality on marginal demand may be either greater or lower than that of average demand, the quality may be distorted either upward or downward. To make sense of MQSs, we focus on situations where a monopolist would want to under-provide quality. In the cases where a monopolist is under-providing quality there is scope for a regulator to step in and set a MQS. So, the regulator might force the monopolist to choose a higher level of quality. However, the optimal quality level depends on how costly it is to increase quality. The key assumption of our model is that the cost of increasing quality is the firm's private information. The regulator only knows the probability distribution of the cost, but its actual realization is only known to the firm. In this asymmetric information setting, there is scope for signalling. We shall show that signalling may take the form of an even more severe under-provision of quality than with the absence of regulation.

The rest of the chapter is structured as follows: Section 3.2 describes the setting of our model, lays out the key assumptions and presents the main results. Section 3.3 concludes the paper.

## 3.2 The Model

Let us examine a two player signalling game, where the players are a monopolist and a benevolent regulator. The firm, having private information regarding the cost of increasing quality, chooses the quality level of its product ( $q$ ) and its quantity ( $x$ ), and the regulator chooses the level of the MQS in order to maximize social welfare. These choices are modelled as a two stage game as follows: In period zero, nature chooses the type of firm. With probability  $m$ , the firm is of high quality with quality parameter  $\alpha_H$ , and with probability  $1 - m$  the firm is of low quality with quality parameter  $\alpha_L$ . At this point in the game, the regulator's beliefs are that the firm is of high (low) quality with probability  $m$  ( $1 - m$ ). These are the regulator's

prior beliefs. In period 1 the firm chooses  $q_1$  and  $x_1$ . Now, the regulator updates his beliefs and let us denote by  $n$  ( $1 - n$ ) the probability that the regulator attaches to the firm being of high (low) quality. These are the regulator's posterior beliefs. In period 2 and after observing the monopolist's choice, the regulator sets the MQS, and the firm chooses  $q_2 \geq \text{MQS}$  and  $x_2$ .

Two periods are needed, in order for the monopolist's choices to be observed by the regulator and for the regulator to react. This is necessary to make sense of signalling. That is, the monopolist's quality choice in the first period can be a signal for the regulator, who has to set a MQS in the second period.

The firm faces an inverse demand function,  $p(x) = q - x$ , where  $p$  denotes the price of the good. The monopolist's variable profits (by normalizing the production cost to zero) are  $\pi_v = x(q - x)$ . From the first order condition, the monopolist's profit maximizing quantity is

$$x = \frac{q}{2} \tag{3.1}$$

which is half of the efficient (competitive) quantity,  $x = q$ . We assume that the cost of providing quality is <sup>3</sup>

$$C = \frac{q^3}{4\alpha} \tag{3.2}$$

where the parameter  $\alpha$  is the firm's private information. It can take on 2 possible values:  $\alpha_H$ , in which case the cost is low and therefore the optimal quality is high, or  $\alpha_L < \alpha_H$  in which case the cost is high and therefore the optimal quality is low. When the regulator makes his choices, he knows the exact value of  $\alpha$ .

The monopolist's profit function, including the cost of increasing quality, is

$$\pi = x(q - x) - \frac{q^3}{4\alpha} \tag{3.3}$$

thus, her discounted profits from the 2 periods are  $\Pi = \pi_1 + b\pi_2$ , where  $\pi_1$  and  $\pi_2$  are the 1st and 2nd period profits respectively, and  $b$  is a parameter that captures the relative weight between the 2 periods.<sup>4</sup> To be more precise, this parameter gives the relative weight between the cost and the benefit of signalling. The cost of

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<sup>3</sup>The reason we are using this cost function is that once the optimal quantity is chosen ( $x = q/2$ ), the maximised profit is quadratic in quality, so we need the cost to be more convex in order for the profit to be concave.

<sup>4</sup> $b$  could be greater than 1, since the periods before and after regulation need not be equal and one would tend to think that what happens after regulation is more important.

signalling is that in period 1 the firm makes a choice which is not statically optimal, which means that in this period the firm loses some profits. Whereas the benefit of signalling is that by acting strategically in period 1, the firm might induce a more favourable choice of the MQS in period 2. Therefore, under certain conditions the firm could get higher profits in period 2 than in the absence of signalling. So,  $b$  shows the relative importance of the gain the firm gets in period 2 versus the cost it has to pay in period 1.

### 3.3 Analysis

#### 3.3.1 Unregulated market equilibrium

Let us first suppose that the innate index of improving quality ( $\alpha$ ) of the monopolist is common knowledge. In a static setting, the monopolist maximizes its profit function  $\pi$  (3.3) w.r.t. quantity and quality. The monopolist's optimal quantity is

$$x^f = \frac{\alpha}{3} \quad (3.4)$$

And optimal quality is

$$q^f = \frac{2\alpha}{3} \quad (3.5)$$

Following Spence (1975), net social welfare ( $W$ ) is equal to consumer surplus,  $CS = \int_0^x (q - s) ds - x(q - x) = qx - \frac{x^2}{2} - x(q - x)$ , plus firm's profits ( $\pi$ ),

$$W = qx - \frac{x^2}{2} - \frac{q^3}{4\alpha} \quad (3.6)$$

#### 3.3.2 First-Best

We assume a completely informed regulator who maximizes the net social welfare function ( $W$ ) with respect to quantity and quality. The socially optimal values for quantity and quality are  $x^o = \frac{4\alpha}{3}$  and  $q^o = \frac{4\alpha}{3}$  respectively. We can see that the quality level is twice as large as the one it would be chosen optimally by a monopolist ( $q^f = \frac{2\alpha}{3}$ ), which means that the firm under-provides quality.

### 3.3.3 Second-Best

Provided that we are in the case where a monopolist under-provides quality, there is an incentive for the perfectly informed regulator to intervene (by setting a MQS, in order to increase quality). However, the regulator cannot set the quality and quantity directly. He can only control quality by means of a MQS. In that case, we have to consider a second best problem in which the quantity ( $x$ ) will always be at the monopoly level,  $x = \frac{q}{2}$ . Conditional on that, the second best social welfare is:

$$W_{SB} = \frac{3q^2}{8} - \frac{q^3}{4\alpha} \quad (3.7)$$

The second best social welfare is what the regulator maximizes because he chooses the quality level knowing that the monopolist will not produce the efficient quantity but the profit maximizing one. Therefore, the complete information second-best maximization of social welfare yields

$$q^* = \alpha$$

Whatever choice of quality will be made, the firm will choose the quantity that maximizes profits. So, the profit function (3.3), given that quantity is chosen optimally (that is for  $x = \frac{q}{2}$ ), is:

$$\pi = x(q - x) - \frac{q^3}{4\alpha} = \frac{q^2}{4} - \frac{q^3}{4\alpha} \quad (3.8)$$

In this complete information setting, a low type firm will choose  $q = \frac{2\alpha_L}{3}$  in the 1st period in order to maximize her profit, thus revealing that  $\alpha = \alpha_L$ . The regulator then in the 2nd period will impose a MQS of  $\alpha_L$ . On the other hand, a high type will choose  $q = \frac{2\alpha_H}{3}$  and the regulator will impose a MQS of  $\alpha_H$ . In both cases, the MQS will be binding as the unconstrained firm would have chosen a lower quality level.

So, the discounted profits of the low type with complete information are:

$$\pi_{Lnosignalling} = \pi_{unregL} + b\pi_{regL} = \frac{\alpha_L^2}{27} \quad (3.9)$$

where  $\pi_{unregL}$  are the profits of the 1st period, where the low type chooses a quality level that statically maximizes its profits (which is  $q = \frac{2\alpha_L}{3}$ ) and  $\pi_{regL}$ <sup>5</sup> are the profits of the 2nd period when the firm is facing a MQS equal to  $\alpha_L$ , which implies that the firm must set its quality equal to the predefined level. Similarly, the high type firm would get discounted profits of:

$$\pi_{Hnosignalling} = \pi_{unregH} + b\pi_{regH} = \frac{\alpha_H^2}{27} \quad (3.10)$$

where  $\pi_{unregH}$  are the 1st period profits (for  $q = \frac{2\alpha_H}{3}$ ) and  $\pi_{regH}$  are the 2nd period profits when the firm is facing a MQS equal to  $\alpha_H$ , with which the firm must comply.

### 3.3.4 Regulated market equilibrium with asymmetric information

Since we are dealing with a sequential game with incomplete information we are going to focus on the perfect Bayesian equilibria of the game. A perfect Bayesian equilibrium requires that each player is sequentially rational, i.e., at a given information set she takes the expected utility maximizing choice given her system of beliefs. A system of beliefs assigns a probability to each state of the world in each information set. In particular, it specifies the probability that the regulator assigns to the firm being of high quality, given its quality choice in period 1. The regulator's beliefs should be in accordance with Bayes' rule (Fudenberg and Tirole, 1991; Tadelis, 2013).

In this incomplete information environment, at the beginning of the 2nd period and after updating his beliefs, the regulator will maximize the following second best social welfare function (he believes with probability  $n$  that  $\alpha$  is  $\alpha_H$ , and with probability  $1 - n$  that  $\alpha$  is  $\alpha_L$ )

$$E(W_{SB}) = n \left( \frac{3q^2}{8} - \frac{q^3}{4\alpha_H} \right) + (1 - n) \left( \frac{3q^2}{8} - \frac{q^3}{4\alpha_L} \right) \quad (3.11)$$

In order to find the level of the MQS he should set, the regulator should take

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<sup>5</sup>For the selected functional forms, when a firm is regulated it makes zero profits, i.e.,  $\pi_{regL} = 0$ . That's why  $b$  is not relevant in the discounted profit function. The same applies for the high type firm's profits under regulation.

into account the participation constraints of a firm. Specifically, if the level of the MQS, with which the monopolist must comply, makes the firm's profits negative, the monopolist will not produce and withdraw from the market, which will affect social welfare.

The quality level that zeroes the monopolist's profit function is  $q = \alpha$ , which means that for MQSs greater than each firm's value for  $\alpha$  ( $\alpha_L$  or  $\alpha_H$ ), the firm will face negative profits. But, the regulator is unsure of the type of firm (low or high quality) the monopolist is. So, if he sets a MQS greater than  $\alpha_L$ , then the low type will not participate (not produce at all). That implies that even if the regulator isn't sure what type the monopolist is, he will set either a MQS at  $\alpha_L$  or  $\alpha_H$ , because if the regulator sets it in an intermediate level, the low type will stay out. At that point there is no reason of decreasing the MQS, which means that the regulator can set it at the participation constraint of the high type,  $\alpha_H$ . If instead, the regulator wants both types to potentially participate, he will set the MQS at  $\alpha_L$ .

Let's analyse how does the regulator update his beliefs from  $m$  to  $n$ . Whatever the low quality firm chooses in the 1st period, it is going to make zero profits in the 2nd period anyway, whether the firm remains in the market when the MQS is set at  $\alpha_L$  or it drops out if it is set at  $\alpha_H$ . So, the regulator knows that in period 1, the low quality firm will always choose its profit maximizing level of quality ( $q_1 = \frac{2\alpha_L}{3}$ ) and could reasonably believe that any quality level  $q_1$  different from  $\frac{2\alpha_L}{3}$  would have to come from the high quality firm. What would the high quality firm choose in that case? If the high type chooses a quality level different from  $\frac{2\alpha_L}{3}$ , since the regulator would know, by observing a quality other than  $q_1 = \frac{2\alpha_L}{3}$  that the firm is of high quality (i.e., his posterior beliefs  $n$  would be equal to 1), he would set a MQS equal to  $\alpha_H$ , leading the firm to zero profit in the 2nd period. Thus, if the high quality firm chose in the 1st period any quality level other than  $\frac{2\alpha_L}{3}$ , it would choose its profit maximizing level of quality,  $\frac{2\alpha_H}{3}$ . If the high type chooses  $q_1 = \frac{2\alpha_L}{3}$ , the adopted levels of quality would be the same for both the high and the low quality firm, and the regulator wouldn't learn anything, which means that his prior beliefs would equal his posterior ones,  $n = m$ . The regulator would then set a MQS equal to  $\alpha_L$  or  $\alpha_H$ , depending on the value of his beliefs  $n = m$ .

At this point, we have to distinguish 2 cases, because the quality an unregulated

high type firm would choose (which is  $q = \frac{2}{3}\alpha_H$ ) might be higher or lower than the smaller of the 2 prospective MQSs ( $\alpha_L$ ), which might have an impact on the 2 players' choices.

Let's assume that  $\frac{2}{3}\alpha_H$  is lower than  $\alpha_L$ . Then, when the MQS is set at  $\alpha_L$ , both types will be active in the market in the 2nd period. Since  $q = \frac{2}{3}\alpha_H < \alpha_L$ , the MQS will be binding for the high type and will have to comply with that. So, social welfare (for  $n = m$  and  $q = \alpha_L$ ) is

$$W_{\alpha_{L1}} = m \left( \frac{3\alpha_L^2}{8} - \frac{\alpha_L^3}{4\alpha_H} \right) + (1 - m) \frac{1}{8} \alpha_L^2 \quad (3.12)$$

If the MQS is set at  $\alpha_H$ , only the high type will be active in the second period and social welfare (for  $n = m$  and  $q = \alpha_H$ ) is:

$$W_{\alpha_{H1}} = m \left( \frac{3q^2}{8} - \frac{q^3}{4\alpha_H} \right) = \frac{\alpha_H^2 m}{8} \quad (3.13)$$

Which policy is best in terms of social welfare,  $a_H$  or  $a_L$ , will depend on the value of the regulator beliefs ( $m$ )

$$W_{\alpha_{H1}} = W_{\alpha_{L1}} \Rightarrow m_1 = \frac{\alpha_H \alpha_L^2}{\alpha_H^3 - 2\alpha_H \alpha_L^2 + 2\alpha_L^3} \quad (3.14)$$

If  $m_1$  is greater than this threshold then it is optimal to have only the high type participate in the market in the 2nd period and so the MQS would be  $\alpha_H$ . If it is lower than the threshold then it is optimal to have both types participate and hence the MQS would be  $\alpha_L$ .

For  $m_1 > \frac{\alpha_H \alpha_L^2}{\alpha_H^3 - 2\alpha_H \alpha_L^2 + 2\alpha_L^3}$ , the regulator would choose a MQS equal to  $\alpha_H$  and the high quality firm would set her 1st period quality equal to  $q = \frac{2}{3}\alpha_H$  in order to maximize its period 1 profit. In that case, its discounted profit is the same as the profit a high quality type would get under complete information,  $\pi_{Hnosignalling} = \frac{\alpha_H^2}{27}$ .

Suppose that  $m_1 < \frac{\alpha_H \alpha_L^2}{\alpha_H^3 - 2\alpha_H \alpha_L^2 + 2\alpha_L^3}$ , which means that the regulator would choose a MQS equal to  $\alpha_L$  and both firms will be active in the market in the 2nd period. In this case, the high type may have an incentive to mimic the low type in the 1st period. Let's calculate the profit that the high type makes by mimicking the low type (that is for  $\alpha = \alpha_H$  and  $q = \frac{2}{3}\alpha_L$ , which is the quality an unregulated low type

firm would choose):

$$\pi_{Hmim} = \frac{q^2}{4} - \frac{q^3}{4\alpha} = \frac{\alpha_L^2}{9} - \frac{2\alpha_L^3}{27\alpha_H} \quad (3.15)$$

**Proposition 7** *When  $b_1$  is large enough then there is a pooling equilibrium, in which the high-type mimics the low-type.*

**Proof** When the MQS is set at  $\alpha_L$  the high type will have to comply with that, so its 2nd period profits (for  $x = \frac{q}{2}$ ,  $\alpha = \alpha_H$ ,  $q = \alpha_L$ ) are:

$$\pi_{regH} = \frac{\alpha_L^2}{4} - \frac{\alpha_L^3}{4\alpha_H} \quad (3.16)$$

Using (3.15) and (3.16) the discounted profit of the high type firm that mimics is

$$\pi_{Hmim1} = \pi_{Hmim} + b_1\pi_{regH} = \frac{\alpha_L^2(3\alpha_H(9b+4) - \alpha_L(27b+8))}{108\alpha_H} \quad (3.17)$$

The high type is indifferent to signal or not when its profits from mimicking the low type (3.17) are equal to the profits from not mimicking (3.10):

$$\pi_{Hmim1} = \pi_{Hnosignalling} \Rightarrow b_1 = \frac{4(\alpha_H^2 + \alpha_H\alpha_L - 2\alpha_L^2)}{27\alpha_L^2}$$

The condition for signalling is that the profit the high type would make by mimicking is greater than the profit it would make by not mimicking,  $\pi_{Hmim1} > \pi_{Hnosignalling}$ . So, whenever  $b_1 > \frac{4(\alpha_H^2 + \alpha_H\alpha_L - 2\alpha_L^2)}{27\alpha_L^2}$ , the high type has an incentive to mimic the low type.

In order to verify that this is indeed an equilibrium, we need to check that when the high type behaves this way, i.e., mimics the low type by choosing  $q_1 = \frac{2}{3}\alpha_L$ , the low type doesn't have an incentive to deviate and change its behaviour (by choosing a different quality level). So, if the low type deviates and chooses  $q_1 > \frac{2}{3}\alpha_L$  (or  $q_1 < \frac{2}{3}\alpha_L$ ) in the 1st period, it would make lower profits (since  $q_1 = \frac{2}{3}\alpha_L$  is the maximizing quality level of her profit function). In the second period and after the MQS is set at  $\alpha_L$  it will make zero profits. Therefore, the low type's discounted profit would be lower compared to the case in which she chose her profit maximizing level of quality in the 1st period. So, it is indeed an equilibrium in which the high

type chooses the same quality level as the low type in the first period and in the second period there is regulation at  $\alpha_L$ .  $\square$

If instead,  $\frac{2}{3}\alpha_H$  is higher than  $\alpha_L$ , a MQS equal to  $\alpha_L$  will no longer be binding for the high quality firm. Then, when the MQS is set at  $\alpha_L$  and both firms remain in the market in the 2nd period, the high type will choose its profit maximizing level of quality  $\frac{2\alpha_H}{3}$  and social welfare (for  $n = m$ ) is

$$W_{\alpha_{L_2}} = \frac{5\alpha_H^2 m}{54} + (1 - m)\frac{1}{8}\alpha_L^2 \quad (3.18)$$

If the MQS is set at  $\alpha_H$ , only the high type will be active in the second period and social welfare would be the same as in the previous case ( $W_{\alpha_{H_1}}$ ).

Again, in order for the regulator to decide which policy is the best,  $a_H$  or  $a_L$ , he will compare the 2 social welfares.

$$W_{\alpha_{H_1}} = W_{\alpha_{L_2}} \Rightarrow m_2 = \frac{27\alpha_L^2}{7\alpha_H^2 + 27\alpha_L^2} \quad (3.19)$$

If  $m_2$  is greater than this threshold the MQS would be  $\alpha_H$ , if it is lower than the threshold the MQS would be  $\alpha_L$ .

For  $m_2 > \frac{27\alpha_L^2}{7\alpha_H^2 + 27\alpha_L^2}$ , the regulator would choose a MQS equal to  $\alpha_H$  and the high quality firm would set her 1st period quality equal to  $q = \frac{2}{3}\alpha_H$  in order to maximize its period 1 profit. In that case, its discounted profit is the same as the profit a high quality type would get under complete information,  $\pi_{Hnosignalling} = \frac{\alpha_H^2}{27}$ .

Suppose that  $m_2 < \frac{27\alpha_L^2}{7\alpha_H^2 + 27\alpha_L^2}$ , which means that the regulator would choose a MQS equal to  $\alpha_L$  and both firms will be active in the 2nd period. Again, there is a chance for the high type to mimic the low type in the 1st period, in which case the high type's profit is  $\pi_{Hmim}$ .

**Proposition 8** *When  $b_2$  is large enough then there is a pooling equilibrium, in which the high-type mimics the low-type.*

**Proof** From (3.15) and its unregulated profit, the discounted profit of the high type firm that mimics is:

$$\pi_{Hmim2} = \pi_{Hmim} + b_2\pi_{unregH} = \frac{\alpha_H^3 b + 3\alpha_H\alpha_L^2 - 2\alpha_L^3}{27\alpha_H} \quad (3.20)$$

The high type is indifferent to signal or not, when its profits from mimicking the low type (3.20) are equal to the profits from not mimicking (3.10):

$$\pi_{Hmim2} = \pi_{Hnosignalling} \Rightarrow b_2 = \frac{\alpha_H^3 - 3\alpha_H\alpha_L^2 + 2\alpha_L^3}{\alpha_H^3}$$

Again, the condition for signalling is that the profit the high type would make by mimicking is greater than the profit it would make by not mimicking ( $\pi_{Hmim2} > \pi_{Hnosignalling}$ ). So, whenever  $b_2 > \frac{\alpha_H^3 - 3\alpha_H\alpha_L^2 + 2\alpha_L^3}{\alpha_H^3}$ , the high type has an incentive to mimic the low type.

In order to verify that this is indeed an equilibrium, we need to check that when the high type behaves this way, i.e., mimics the low type by choosing  $q_1 = \frac{2}{3}\alpha_L$ , the low type doesn't have an incentive to deviate and change its behaviour (by choosing a different quality level). So, if the low type deviates and chooses  $q_1 > \frac{2}{3}\alpha_L$  (or  $q_1 < \frac{2}{3}\alpha_L$ ) in the 1st period, it would make lower profits (since  $q_1 = \frac{2}{3}\alpha_L$  is the maximizing quality level of her profit function). In the second period and after the MQS is set at  $\alpha_L$  it will make zero profits. Therefore, the low type's discounted profit would be lower compared to the case in which she chose her profit maximizing level of quality in the 1st period. So, it is indeed an equilibrium in which the high type chooses the same quality level as the low type in the first period and in the second period there is regulation at  $\alpha_L$ .  $\square$

In this framework, the low type would never want to signal that it is the high type. Because, the MQS will be set at  $\alpha_L$ , it would make zero profits anyway. Either no one behaves strategically, so we are in a separating equilibrium or there is a pooling equilibrium (because the low type behaves sincerely, so if the high type wants to get into a separating equilibrium, it just have to do nothing).

Furthermore, we can perform a welfare analysis in order to examine whether there are cases for which social welfare in an unregulated market may be greater than the one in a regulated market. Our conjecture is that there should be different sets of parameter values for which such a case arise. Even though a formal proof of this remains for future work, a simplified illustrative example is presented in the appendix (see chapter 4.2).

### 3.4 Conclusion

The purpose of the present paper was to explore how the MQS choice of a welfare-maximizing regulator can be altered in a framework of asymmetric information, in which the regulator does not have the leader advantage. The asymmetry of information relates to the cost of improving the quality that the high quality monopolist would want to signal, and it is assumed that the policy maker has only a probability distribution regarding this cost. By constructing a two-period signalling model with two players -a monopolist and a regulator- we have shown that the presence of the MQS setting regulator creates negative impacts on quality choices, that distort the optimal quality choice. The reason is that firms may have an incentive to decrease their quality levels in order to signal to the regulator that it is too costly to increase quality. And if the monopolist manages to disguise itself as the high cost firm by mimicking him, the MQS will be downward distorted, which, under certain circumstances, might affect social welfare. The main policy implication of the paper is that a regulator may optimally pledge not to intervene by setting a MQS, owing to the fact that social welfare could be higher if compared to the situation where the regulator steps in. Certainly, one could think of various types of qualities that our result can be applied to, like for example the environmental quality of the production technology of a good. An interesting extension of the paper, that might enrich the existing results and widen their economics and policy implications, can be a model of duopolistic competition with endogenous (vertical) product qualities.

# Conclusion

This thesis discusses issues such as growth, crime, and policy tools with a particular interest in how they impact environmental quality.

In Chapter 1, we have investigated the relationship between human capital accumulation and health damaging pollution. We have shown that for low income economies, where the effect of income on pollution is positive and monotonic, the impact of pollution on health can negatively influence the dynamics of the economy, which will cyclically converge to an equilibrium with zero growth. For higher income economies, we observe a negative relation between income and pollution, i.e., we verify the presence of an Environmental Kuznets Curve and find that as income increases, pollution will eventually decrease which means that health will be consequently ameliorated. This will reinforce the positive effect of current income on future income and possibly lead to positive growth. The starting conditions with respect to human capital, i.e., whether we have a lower or a higher income economy, determine the long-run prospects of the economy. The presence of a policy parameter, namely the environmental tax, can create conditions under which in the high income equilibrium there is a decline in pollution.

In Chapter 2, we have explored whether the occurrence of crime can affect entrepreneurs economic incentives to invest in pollution abatement technologies. It is shown that current differences in criminal activity can persist in the long-run, due to social norms, and can have implications not only for output but for the environment as well. Depending on the values of parameters, we have demonstrated that there exists a situation in which a high crime economy that produces less, actually has higher pollution. This is explained by the fact that since there is a fixed cost of obtaining the environmentally friendly technology and since criminal groups extort a fraction of the firms' variable profit, in the presence of crime a smaller number of

entrepreneurs would be willing to adopt the cleaner technology, which will increase emission intensity and consequently pollution. In terms of policy implications, a regulation against crime might have widespread implications not only for the reduction of criminal activity per se, but for improvements of environmental quality as well.

Finally, in Chapter 3, we have examined how the MQS choice of a welfare maximizing regulator can be altered in a framework of asymmetric information, in which the regulator does not have the leader advantage. The asymmetry of information relates to the cost of improving the quality that the high quality monopolist would want to signal, and it is assumed that the policy maker has only a probability distribution regarding this cost. We have shown that with a MQS, the aggregate quality may actually be lower than it would have been without any regulation. The policy implication of our result is that, under certain circumstances, the regulator may optimally choose to pre-commit not to regulate, as in this case social welfare could be higher than in the scenario where the regulator is free to step in.

In brief, this thesis provides insight into the aforementioned topics regarding environmental quality and the ensuing policy implications, as well as fruitful avenues for future research to pursuit.

# Appendices

# Chapter 4

## Appendices

### 4.1 Appendix to chapter 1

#### 4.1.1 Proof of lemma 1

**Proof** From Eqs. (1.19) and (1.20) we get:

$$A^2T^2(\phi\beta - \gamma)(1 - \eta)h_t^2 - pAh_t + (\phi\beta - \gamma)(1 - \eta) = 0 \quad (4.1)$$

As long as the tax rate is positive ( $T > 0$ ), the expression in (4.1) is a quadratic equation that will change sign once. The 2 roots are:

$$\hat{h}_{1,2} = \frac{p \pm \sqrt{p^2 - (2T(\phi\beta - \gamma)(1 - \eta))^2}}{2AT^2(\phi\beta - \gamma)(1 - \eta)} \quad (4.2)$$

Defining the composite term  $\Psi = 2T(\phi\beta - \gamma)(1 - \eta)$ , we obtain:

$$\hat{h}_1 = \frac{p - \sqrt{p^2 - \Psi^2}}{AT\Psi}, \quad \hat{h}_2 = \frac{p + \sqrt{p^2 - \Psi^2}}{AT\Psi} \quad (4.3)$$

For the 2 roots to be real numbers,  $p^2 - \Psi^2 > 0 \Rightarrow T < \frac{p}{2(\phi\beta - \gamma)(1 - \eta)}$ , and to guarantee that there is an equilibrium the following condition needs to hold:  $T < \min[\frac{p}{2(\phi\beta - \gamma)(1 - \eta)}, 1]$ . For  $T > \frac{p}{2(\phi\beta - \gamma)(1 - \eta)}$ , (4.1) has no real roots, which means that there is no such thing as a steady state equilibrium. That's why we rule out this possibility.

Therefore the 2 pairs of the steady state equilibria (from Eqs. (1.20) and (4.3))

are:

$$\hat{\mu} = \phi\beta - \gamma, \quad \hat{h}_1 = \frac{p - \sqrt{p^2 - \Psi^2}}{AT\Psi}$$

and

$$\hat{\mu} = \phi\beta - \gamma, \quad \hat{h}_2 = \frac{p + \sqrt{p^2 - \Psi^2}}{AT\Psi}$$

The next step of our analysis is to determine the stability of the 2 pairs of equilibria. We know that the stability type of a steady state depends on the eigenvalues of the Jacobian matrix of partial derivatives. The Jacobian matrix associated with the system of difference equations in Eqs. (1.17) and (1.18) is the following:

$$J = \begin{pmatrix} H_{h_t}(\hat{h}, \hat{\mu}) & H_{\mu_t}(\hat{h}, \hat{\mu}) \\ M_{h_t}(\hat{h}, \hat{\mu}) & M_{\mu_t}(\hat{h}, \hat{\mu}) \end{pmatrix}$$

where  $h_{t+1} = H(h_t, \mu_t)$ ,  $\mu_{t+1} = M(h_t, \mu_t)$  and  $\hat{h}$  and  $\hat{\mu}$  are the steady state values for  $h$  and  $\mu$  respectively. Note that:

$$\begin{aligned} H_{h_t}(\hat{h}, \hat{\mu}) &= 1 \\ H_{\mu_t}(\hat{h}, \hat{\mu}) &= \frac{-\hat{h}}{\phi\beta} \\ M_{h_t}(\hat{h}, \hat{\mu}) &= \frac{Ap(1-(AT\hat{h})^2)}{(1+(AT\hat{h})^2)^2} \\ M_{\mu_t}(\hat{h}, \hat{\mu}) &= \eta \end{aligned}$$

The eigenvalues of the Jacobian matrix are the roots of the characteristic polynomial,  $p(\lambda) = \lambda^2 - \lambda T + D = 0$ , where T and D are the trace and determinant of the Jacobian matrix respectively. The Jacobian matrix trace and its determinant are given by the following:

$$T = 1 + \eta \tag{4.4}$$

$$D = \eta + \frac{\hat{h}}{\phi\beta} \frac{Ap(1-(AT\hat{h})^2)}{(1+(AT\hat{h})^2)^2} = \eta + \frac{\hat{h}}{\phi\beta} \frac{Ap}{(1+(AT\hat{h})^2)} \frac{(1-(AT\hat{h})^2)}{(1+(AT\hat{h})^2)} \tag{4.5}$$

For  $\mu_{t+1} = \mu_t = \hat{\mu}$  and  $h_{t+1} = h_t = \hat{h}$ , equation (1.19) becomes:

$$\frac{pA\hat{h}}{(1+(TA\hat{h})^2)} = \hat{\mu}(1 - \eta) \tag{4.6}$$

From (1.20) and (4.6), we get:

$$\frac{pA\hat{h}}{(1 + (TA\hat{h})^2)} = (\phi\beta - \gamma)(1 - \eta) \quad (4.7)$$

Using (4.7), the determinant (4.5) becomes:

$$D = \eta + \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - (AT\hat{h})^2)}{(1 + (AT\hat{h})^2)} \quad (4.8)$$

Setting  $AT\hat{h} = X$  equation (4.8) becomes:

$$D = \eta + \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)} \quad (4.9)$$

The eigenvalues are real if and only if  $\Delta \geq 0$  (where  $\Delta$  is the discriminant of the characteristic polynomial) and are complex otherwise.

$$\Delta = T^2 - 4D = (1 + \eta)^2 - 4\eta - 4 \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)} \quad (4.10)$$

For the high income steady state  $\hat{h} = \hat{h}_2$ , it holds that:  $\hat{h}_2 > \frac{1}{AT} \Rightarrow AT\hat{h}_2 > 1 \Rightarrow X > 1 \Rightarrow X^2 > 1 \Rightarrow 1 - X^2 < 0$ , where  $\frac{1}{AT}$  is the value of human capital that maximizes the  $\Delta\mu_t = 0$  curve. This means that  $\Delta = T^2 - 4D > 0$  and therefore the eigenvalues are real.

In order to infer whether the steady state is a sink, a source or a saddle point, we need to find the sign of  $p(1)$  and  $p(-1)$ :

$$p(1) = 1 - T + D \quad (4.11)$$

From equations (4.4) and (4.9) we get:

$$p(1) = 1 - 1 - \eta + \eta + \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)} = \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)}$$

$$p(-1) = 1 + T + D \quad (4.12)$$

Again using equations (4.4) and (4.9) we get:

$$p(-1) = 2 + 2\eta + \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)}$$

It is straightforward to show that:  $p(1) < 0$  and  $p(-1) > 0$ , which means that the steady state is a saddle point. In other words there is saddle path stability and the equilibrium is unstable.

For the low income steady state  $\hat{h} = \hat{h}_1$ , it holds that:

$\hat{h}_1 < \frac{1}{AT} \Rightarrow AT\hat{h}_1 < 1 \Rightarrow X < 1 \Rightarrow X^2 < 1 \Rightarrow 1 - X^2 > 0$ , which means that  $T^2 - 4D \leq 0$ .

Let's assume that:

$$\begin{aligned} T^2 - 4D < 0 &\Rightarrow (1 + \eta)^2 - 4\eta - 4 \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)} < 0 \Rightarrow \\ &\Rightarrow (1 - \eta)^2 - 4 \frac{(\phi\beta - \gamma)(1 - \eta)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)} < 0 \Rightarrow \\ &\Rightarrow (1 - \eta) \left[ (1 - \eta) - 4 \frac{(\phi\beta - \gamma)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)} \right] < 0 \Rightarrow \\ &\Rightarrow (1 - \eta) - 4 \frac{(\phi\beta - \gamma)}{\phi\beta} \frac{(1 - X^2)}{(1 + X^2)} < 0 \end{aligned}$$

For the inequality to be valid we need to assume that  $p > \frac{4}{\sqrt{3}}T(\phi\beta - \gamma)(1 - \eta)$  and therefore the eigenvalues are complex.

It is straightforward to show that  $D < 1$ , which means that the low income steady state is asymptotically (locally) stable (or a sink) and/or is related to stable spirals.  $\square$

## 4.2 Appendix to chapter 3

### 4.2.1 Welfare analysis example

Let's assume that  $\frac{2}{3}\alpha_H < \alpha_L$ . Then, for  $m_1 < \frac{\alpha_H\alpha_L^2}{\alpha_H^3 - 2\alpha_H\alpha_L^2 + 2\alpha_L^3}$ , the regulator would choose a MQS equal to  $\alpha_L$  and both firms will be active in the market in the 2nd period. The two period social welfare taking into account only the high type who is mimicking the low type in the 1st period and adopting a quality level equal to the

MQS in the 2nd period (i.e., for  $q_1 = \frac{2\alpha_L}{3}$  and  $q_2 = \alpha_L$ , and  $\alpha = \alpha_H$ ) is

$$W_H = \left( \frac{3\left(\frac{2\alpha_L}{3}\right)^2}{8} - \frac{\left(\frac{2\alpha_L}{3}\right)^3}{4\alpha_H} \right) + b \left( \frac{3(\alpha_L)^2}{8} - \frac{(\alpha_L)^3}{4\alpha_H} \right) \quad (4.13)$$

The two period social welfare taking into account only the low type who is adopting her profit maximizing level of quality in the 1st period and a quality level equal to the MQS in the 2nd period (i.e., for  $q_1 = \frac{2\alpha_L}{3}$  and  $q_2 = \alpha_L$ , and  $\alpha = \alpha_L$ ) is

$$W_L = \left( \frac{3\left(\frac{2\alpha_L}{3}\right)^2}{8} - \frac{\left(\frac{2\alpha_L}{3}\right)^3}{4\alpha_L} \right) + b \left( \frac{3(\alpha_L)^2}{8} - \frac{(\alpha_L)^3}{4\alpha_L} \right) \quad (4.14)$$

Taking into account the regulator's beliefs ( $m$  and  $1 - m$ ), the ex ante social welfare of the regulated market is  $EW_r = mW_H + (1 - m)W_L$ , or

$$EW_r = m \left( \left( \frac{3\left(\frac{2\alpha_L}{3}\right)^2}{8} - \frac{\left(\frac{2\alpha_L}{3}\right)^3}{4\alpha_H} \right) + b \left( \frac{3(\alpha_L)^2}{8} - \frac{(\alpha_L)^3}{4\alpha_H} \right) \right) + (1 - m) \left( \left( \frac{3\left(\frac{2\alpha_L}{3}\right)^2}{8} - \frac{\left(\frac{2\alpha_L}{3}\right)^3}{4\alpha_L} \right) + b \left( \frac{3(\alpha_L)^2}{8} - \frac{(\alpha_L)^3}{4\alpha_L} \right) \right) \quad (4.15)$$

When there isn't any regulation, both firms will choose their profit maximizing levels of quality in both periods (i.e., the low type will choose  $q_1 = q_2 = \frac{2\alpha_L}{3}$  and the high type  $q_1 = q_2 = \frac{2\alpha_H}{3}$ ). Taking into account the regulator's beliefs ( $m$  and  $1 - m$ ), the ex ante social welfare of the unregulated market is

$$EW_u = m(1 + b) \left( \frac{3\left(\frac{2\alpha_H}{3}\right)^2}{8} - \frac{\left(\frac{2\alpha_H}{3}\right)^3}{4\alpha_H} \right) + (1 - m)(1 + b) \left( \frac{3\left(\frac{2\alpha_L}{3}\right)^2}{8} - \frac{\left(\frac{2\alpha_L}{3}\right)^3}{4\alpha_L} \right) \quad (4.16)$$

We can show that the difference between  $EW_r$  and  $EW_u$  can be negative (i.e.,  $\Delta W = EW_r - EW_u < 0$ ) by substituting the following parameter values,  $\alpha_H = 3$ ,  $\alpha_L = 1$ ,  $m = 0.1$  and  $b = 1.7$ . This will yield  $\Delta W = -0.111636$ , thus verifying that, under certain circumstances, social welfare can be lower under regulation compared to the case of an unregulated market.

# Bibliography

- Akerlof, G. A. and Yellen, J. L. (1993). *Crime and punishment in a social setting: an economic model of inner city gangs*. Canadian Institute for Advanced Research.
- Alonso-Carrera, J. and Freire-Serén, M. J. (2004). Multiple equilibria, fiscal policy, and human capital accumulation. *Journal of Economic Dynamics and Control*, 28(4):841–856.
- Andreoni, J. and Levinson, A. (2001). The simple analytics of the environmental kuznets curve. *Journal of public economics*, 80(2):269–286.
- Arora, S. and Gangopadhyay, S. (1995). Toward a theoretical model of voluntary overcompliance. *Journal of economic behavior & organization*, 28(3):289–309.
- Azomahou, T., Laisney, F., and Van, P. N. (2006). Economic development and co 2 emissions: a nonparametric panel approach. *Journal of Public Economics*, 90(6):1347–1363.
- Baron, D. P. and Besanko, D. (1984a). Regulation and information in a continuing relationship. *Information Economics and policy*, 1(3):267–302.
- Baron, D. P. and Besanko, D. (1984b). Regulation, asymmetric information, and auditing. *RAND Journal of Economics*, 15(4):447–470.
- Baron, D. P. and Myerson, R. B. (1982). Regulating a monopolist with unknown costs. *Econometrica*, 50(4):911–930.
- Becker, G. S. (1968). Crime and punishment: An economic approach. *Journal of Political Economy*, 76(2):169–217.
- Bisin, A. and Verdier, T. (2001). The economics of cultural transmission and the dynamics of preferences. *Journal of Economic Theory*, 97(2):298 – 319.

- Blackburn, K., Neanidis, K. C., and Rana, M. P. (2017). A theory of organized crime, corruption and economic growth. *Economic Theory Bulletin*, 5(2):227–245.
- Blackburn, K. and Varvarigos, D. (2008). Human capital accumulation and output growth in a stochastic environment. *Economic Theory*, 36(3):435–452.
- Blankenau, W. and Camera, G. (2009). Public spending on education and the incentives for student achievement. *Economica*, 76(303):505–527.
- Braeutigam, R. R. (1989). Optimal policies for natural monopolies. *Handbook of industrial organization*, 2:1289–1346.
- Buehler, B. and Schuett, F. (2014). Certification and minimum quality standards when some consumers are uninformed. *European Economic Review*, 70:493–511.
- Burdett, K., Lagos, R., and Wright, R. (2003). Crime, inequality, and unemployment. *American Economic Review*, 93(5):1764–1777.
- Caballé, J. and Santos, M. S. (1993). On endogenous growth with physical and human capital. *Journal of Political Economy*, 101(6):1042–1067.
- Calvo-Armengol, A., Verdier, T., and Zenou, Y. (2007). Strong and weak ties in employment and crime. *Journal of Public Economics*, 91(1):203 – 233.
- Cárdenas, M. and Rozo, S. (2008). *Does Crime Lower Growth?: Evidence from Colombia*. International Bank for Reconstruction and Development/The World Bank.
- Case, A. C., Katz, L. F., et al. (1991). The company you keep: The effects of family and neighborhood on disadvantaged youths. Technical report, National Bureau of Economic Research, Inc.
- Crampes, C. and Hollander, A. (1995). Duopoly and quality standards. *European Economic Review*, 39(1):71–82.
- D’Amato, A., Mazzanti, M., and Nicolli, F. (2015). Waste and organized crime in regional environments. *Resource and Energy Economics*, 41(C):185–201.
- D’Amato, A. and Zoli, M. (2012). Illegal waste disposal in the time of the mafia:

- a tale of enforcement and social well being. *Journal of Environmental Planning and Management*, 55(5):637–655.
- Daniele, V. and Marani, U. (2008). Organized crime and foreign direct investment: the italian case. *Trends in Organized Crime*, 11(3):296–300.
- Daniels, M. J., Dominici, F., Samet, J. M., and Zeger, S. L. (2000). Estimating particulate matter-mortality dose-response curves and threshold levels: an analysis of daily time-series for the 20 largest us cities. *American journal of epidemiology*, 152(5):397–406.
- Denicolo, V. (2008). A signaling model of environmental overcompliance. *Journal of Economic Behavior & Organization*, 68(1):293–303.
- Detotto, C. and Otranto, E. (2010). Does crime affect economic growth? *Kyklos*, 63(3):330–345.
- Dockery, D. W., Pope, C. A., Xu, X., Spengler, J. D., Ware, J. H., Fay, M. E., Ferris Jr, B. G., and Speizer, F. E. (1993). An association between air pollution and mortality in six us cities. *New England journal of medicine*, 329(24):1753–1759.
- Ecchia, G. and Lambertini, L. (1997). Minimum quality standards and collusion. *The Journal of Industrial Economics*, 45(1):101–113.
- Enamorado, T., López-Calva, L. F., and Rodríguez-Castelán, C. (2014). Crime and growth convergence: Evidence from mexico. *Economics Letters*, 125(1):9–13.
- Evans, M. F. and Smith, V. K. (2005). Do new health conditions support mortality–air pollution effects? *Journal of Environmental Economics and Management*, 50(3):496–518.
- Fajnzylber, P., Lederman, D., and Loayza, N. (1998). *Determinants of crime rates in Latin America and the world: an empirical assessment*. World Bank Publications.
- Fajnzylber, P., Lederman, D., and Loayza, N. (2002). What causes violent crime? *European Economic Review*, 46(7):1323–1357.
- Freire, C., Ramos, R., Puertas, R., Lopez-Espinosa, M.-J., Julvez, J., Aguilera, I., Cruz, F., Fernandez, M.-F., Sunyer, J., and Olea, N. (2010). Association of

- traffic-related air pollution with cognitive development in children. *Journal of epidemiology and community health*, 64(3):223–228.
- Fudenberg, D. and Tirole, J. (1991). *Game Theory*. MIT press, Boston MA.
- Garella, P. G. and Petrakis, E. (2008). Minimum quality standards and consumers information. *Economic Theory*, 36(2):283–302.
- Gaviria, A. (2002). Assessing the effects of corruption and crime on firm performance: evidence from latin america. *Emerging Markets Review*, 3(3):245–268.
- Glaeser, E. L., Sacerdote, B., and Scheinkman, J. A. (1996). Crime and social interactions. *The Quarterly Journal of Economics*, 111(2):507–548.
- Goglio, S. (2004). Crime, collective action and development. *European Planning Studies*, 12(6):853–869.
- Gradus, R. and Smulders, S. (1993). The trade-off between environmental care and long-term growthpollution in three prototype growth models. *Journal of Economics*, 58(1):25–51.
- Greiner, A. and Semmler, W. (2002). Externalities of investment, education and economic growth. *Economic Modelling*, 19(5):709–724.
- Grimaud, A. (1999). Pollution permits and sustainable growth in a schumpeterian model. *Journal of Environmental Economics and Management*, 38(3):249–266.
- Grimaud, A. and Tournemaine, F. (2007). Why can an environmental policy tax promote growth through the channel of education? *Ecological Economics*, 62(1):27–36.
- Grossman, G. M. and Krueger, A. B. (1994). Economic growth and the environment. Technical report, National Bureau of Economic Research.
- Hallward-Driemeier, M. and Stewart, D. (2004). How do investment climate conditions vary across countries, regions and types of firms? *background paper prepared for the World Development Report, The World Bank, Washington, DC*.
- Hettich, F. (1998). Growth effects of a revenue-neutral environmental tax reform. *Journal of Economics*, 67(3):287–316.

- Huang, C. C., Laing, D., and Wang, P. (2004). Crime and poverty: A search theoretic approach. *International Economic Review*, 45(3):909–938.
- John, A. and Pecchenino, R. (1994). An overlapping generations model of growth and the environment. *The Economic Journal*, 104(427):1393–1410.
- Jouvet, P.-A., Pestieau, P., and Ponthiere, G. (2010). Longevity and environmental quality in an oig model. *Journal of Economics*, 100(3):191–216.
- Kan, H., London, S. J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L., and Chen, B. (2008). Season, sex, age, and education as modifiers of the effects of outdoor air pollution on daily mortality in shanghai, china: The public health and air pollution in asia (papa) study. *Environmental health perspectives*, 116(9):1183.
- Konrad, K. I. and Skaperdas, S. (1998). Extortion. *Economica*, 65(260):461–477.
- Krkoska, L. and Robeck, K. (2006). The impact of crime on the enterprise sector: Transition versus non-transition countries. working paper no 97. *EBRD - Publications*.
- Kroft, K. and Lloyd-Ellis, H. (2002). Further cross-country evidence on the link between growth, volatility and business cycles. *University of California, Berkeley*.
- Lavy, V., Ebenstein, A., and Roth, S. (2014). The impact of short term exposure to ambient air pollution on cognitive performance and human capital formation. Technical report, National Bureau of Economic Research.
- Leland, H. E. (1979). Quacks, lemons, and licensing: A theory of minimum quality standards. *The journal of political economy*, pages 1328–1346.
- Lucas, R. E. (1988). On the mechanics of economic development. *Journal of monetary economics*, 22(1):3–42.
- Lutz, S., Lyon, T. P., and Maxwell, J. W. (2000). Quality leadership when regulatory standards are forthcoming. *The Journal of Industrial Economics*, 48(3):331–348.
- Margulis, S. (1991). A guide to back of the envelope estimates of environmental damage costs: An application to mexico. Technical report, Mimeo, World Bank.

- Mariani, F., Pérez-Barahona, A., and Raffin, N. (2010). Life expectancy and the environment. *Journal of Economic Dynamics and Control*, 34(4):798–815.
- Martin, P. and Rogers, C. A. (2000). Long-term growth and short-term economic instability. *European Economic Review*, 44(2):359–381.
- Maxwell, J. W. (1998). Minimum quality standards as a barrier to innovation. *Economics Letters*, 58(3):355–360.
- Maxwell, J. W., Lyon, T. P., and Hackett, S. C. (2000). Self-regulation and social welfare: The political economy of corporate environmentalism\*. *The Journal of Law and Economics*, 43(2):583–618.
- OECD (2007). *Business and the Environment: Policy Incentives and Corporate Responses*. Organisation for Economic Co-operation and Development.
- Palivos, T. and Varvarigos, D. (2017). Pollution abatement as a source of stabilization and long-run growth. *Macroeconomic Dynamics*, 21(3):644–676.
- Panayotou, T. et al. (1993). Empirical tests and policy analysis of environmental degradation at different stages of economic development. Technical report, International Labour Organization.
- Pautrel, X. (2008). Reconsidering the impact of the environment on long-run growth when pollution influences health and agents have a finite-lifetime. *Environmental and Resource Economics*, 40(1):37–52.
- Peri, G. (2004). Socio-cultural variables and economic success: evidence from italian provinces 1951-1991. *Topics in Macroeconomics*, 4(1).
- Pope III, C. A., Burnett, R. T., Thun, M. J., Calle, E. E., Krewski, D., Ito, K., and Thurston, G. D. (2002). Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *Journal of the American Medical Association*, 287(9):1132–1141.
- Pope III, C. A., Thun, M. J., Namboodiri, M. M., Dockery, D. W., Evans, J. S., Speizer, F. E., and Heath Jr, C. W. (1995). Particulate air pollution as a predictor of mortality in a prospective study of us adults. *American journal of respiratory and critical care medicine*, 151(3\_pt\_1):669–674.

- Popp, D. (2002). Induced innovation and energy prices. *The American Economic Review*, 92(1):160–180.
- Raffin, N. and Seegmuller, T. (2014). Longevity, pollution and growth. *Mathematical Social Sciences*, 69:22–33.
- Raffin, N. and Seegmuller, T. (2017). The cost of pollution on longevity, welfare and economic stability. *Environmental and Resource Economics*, 68(3):683–704.
- Ramey, G. and Ramey, V. A. (1995). Cross-country evidence on the link between volatility and growth. *The American Economic Review*, 85(5):1138–1151.
- Rasmusen, E. (1996). Stigma and self-fulfilling expectations of criminality. *The Journal of Law and Economics*, 39(2):519–543.
- Rebelo, S. T. (1990). Long run policy analysis and long run growth. Technical report, National Bureau of Economic Research.
- Roland, G. and Verdier, T. (2003). Law enforcement and transition. *European Economic Review*, 47(4):669 – 685.
- Ronnen, U. (1991). Minimum quality standards, fixed costs, and competition. *RAND Journal of Economics*, 22(4):490–504.
- Samet, J. M., Dominici, F., Curriero, F. C., Coursac, I., and Zeger, S. L. (2000). Fine particulate air pollution and mortality in 20 us cities, 1987–1994. *New England journal of medicine*, 343(24):1742–1749.
- Scarpa, C. (1998). Minimum quality standards with more than two firms. *International Journal of Industrial Organization*, 16(5):665–676.
- Schrag, J. and Scotchmer, S. (1997). The self-reinforcing nature of crime. *International Review of Law and Economics*, 17(3):325–335.
- Shafik, N. and Bandyopadhyay, S. (1992). *Economic growth and environmental quality: time-series and cross-country evidence*, volume 904. World Bank Publications.
- Shapiro, C. (1983). Premiums for high quality products as returns to reputations. *The Quarterly Journal of Economics*, 98(4):659–679.

- Shavell, S. (1993). An economic analysis of threats and their illegality: blackmail, extortion, and robbery. *University of Pennsylvania Law Review*, 141(5):1877–1903.
- Smulders, S. and Gradus, R. (1996). Pollution abatement and long-term growth. *European Journal of Political Economy*, 12(3):505–532.
- Spence, A. M. (1975). Monopoly, quality, and regulation. *The Bell Journal of Economics*, 6(2):417–429.
- Tadelis, S. (2013). *Game theory: An Introduction*. Princeton University Press.
- Tirole, J. (1988). *The theory of industrial organization*. MIT press.
- Valletti, T. M. (2000). Minimum quality standards under cournot competition. *Journal of Regulatory Economics*, 18(3):235–245.
- Van Ewijk, C. and Van Wijnbergen, S. (1995). Can abatement overcome the conflict between environment and economic growth? *De Economist*, 143(2):197–216.
- Varvarigos, D. (2010). Environmental degradation, longevity, and the dynamics of economic development. *Environmental and Resource Economics*, 46(1):59–73.
- Varvarigos, D. (2014). Endogenous longevity and the joint dynamics of pollution and capital accumulation. *Environment and Development Economics*, 19(4):393–416.
- WHO (2016). *World Health Statistics 2016: Monitoring Health for the SDGs Sustainable Development Goals*. World Health Organization.