Center
for
Economic Research

No. 2000-95

EXPLAINING ENVIRONMENTAL KUZNETS CURVES: HOW POLLUTION INDUCES POLICY AND NEW TECHNOLOGIES

By Sjak Smulders and Lucas Bretschger

October 2000

ISSN 0924-7815

Explaining Environmental Kuznets Curves: How Pollution Induces Policy and New Technologies

Sjak Smulders*
and
Lucas Bretschger**

September 2000

Abstract
Production often causes pollution as a by-product. Once pollution problems become too severe, regulation is introduced by political authorities which forces the economy to make a transition to cleaner production processes. We model this transition as a change in "general purpose technology" (GPT) and investigate how it interferes with economic growth driven by quality-improvements. The model gives an explanation for the inverted U-shaped relationship found in empirical research for many pollutants, often referred to as the Environmental Kuznets Curve (EKC). We provide an analytical foundation for the claim that the rise and decline of pollution can be explained by policy-induced technology shifts.

Key words: Environmental Kuznets curve, general purpose technology, growth.

JEL Codes: O41, Q20.

* Corresponding author: Department of Economics, Tilburg University, P.O.Box 90153, 5000 LE Tilburg, The Netherlands, j.a.smulders@kub.nl.
** Ernst-Moritz-Arndt-Universität, Greifswald, Friedrich-Loeffler-Str. 70, 17487 Greifswald, Germany, Lucas.Bretschger@uni-greifswald.de.

Smulders' research is supported by the Royal Dutch Academy of Arts and Sciences. We thank Richard Nahuis and Participants of the workshop Dynamique Economique et des Preoccupations Environmentales , University Paris-X, June 2000.

1. Introduction

An old, classical, and recurring theme in economics is the relationship between economic growth and public concern for environmental problems. It ranges from the physiocrats focus on land, Jevon s coal question, and the Club of Rome s doomsday scenarios to the current greenhouse gas problem. In recent literature, the relationship between economic development and pollution has been widely discussed. For many pollutants, an inverted-U-shaped relationship between per capita income and pollution, labeled the *Environmental Kuznets Curve (EKC)*, is documented.[1] Concentration of a certain pollutant typically first increases with production, which reflects a scale effect, but later on, emissions are de-linked from income.

Hypotheses to explain this de-linking of pollution from growth are either the assumption of a shift in the composition of production (from manufacturing to services), or a change in techniques used.[2] Especially the latter change is likely to be policy-induced. If the environment is a normal good of which demand increases with income, higher income levels trigger more stringent environmental policies that induce firms to change technology. This kind of de-linking is thus achieved due to the combination of political correction of market failures and technological change. Before policy-induced technical change can arise, policy concerning environmental issues has to be shaped. Growing evidence of harmful effects and new findings by natural scientists have a large impact on public concern about the environment and may result eventually in new environmental policy measures. Examples of rather late policy reactions to growing evidence of potential problems are the greenhouse and nuclear power problems. In sum, new information about ecological problems, the implementation of policy measures, and new technological possibilities are at the heart of the EKC.

Until now, there is a large empirical literature on EKCs, see Seldon and Song (1994), Shafik (1994), Cropper and Griffiths (1994), Grossman and Krueger (1995) and Hilton and Levinson (1998) in particular. But it is surprising that the theoretical literature on environmental growth models does not say much about the phenomenon.[3] In general, the theory of growth tends to focus on balanced growth paths which seems difficult to combine with the non-linear nature of the EKC. Yet, the theory of endogenous growth exactly provides those building blocks that are needed to seriously study the interaction between growth, technology and environment. One of the exceptions is Stockey (1998) who presents a model of growth and pollution in which relatively high marginal abatement costs for the first units of abatement makes poor countries to abstain from abatement activities. De Groot (1999) gives another growth-theoretical

[1] See, for example, the special issues of Environment and Development Economics 1997 and Ecological Economics 1998, and the survey article by De Bruyn 1999.
[2] See Copeland and Taylor (AER 1994) for the distinction between scale, composition and technique effects.
[3] See Smulders 1995 and 1999 for a survey on environmental growth models and Bretschger 1999 for the integration of natural resource use into modern growth theory.

explanation for the EKC. In his model, endogenous sectoral changes, driven by income effects and learning-by-doing, generate the EKC pattern. This mechanism, however, seems less relevant for mature economies in which intersectoral shifts are of minor importance relative to intrasectoral changes. Empirical decomposition studies confirm the overwhelming dominance of intra-sectoral changes (Torvanger 1991, De Bruyn 1997, and 1999 p. 88). Finally, Andreoni and Levinson (2000) present a simple model of the EKC driven by income effects. Their approach, however, does not explicitly model economic growth or technological change.

This paper aims to link the empirical evidence on the interaction between economic growth and environmental problems to theories of technological change and economic growth. Specifically, it explains the EKC in an endogenous growth model with three key elements. First, technological change allows for reductions in pollution. Second, intrasectoral shifts accompany the adoption of pollution-reducing technologies. Third, technical change and sectoral shifts are both driven by policy changes, which in turn occur at discrete times and reflect awareness of environmental problems.

Pollution-saving inventions arise in clusters at discrete times; it is costly to adopt them. They can be interpreted as *general purpose technologies (GPT)*, defined by Bresnahan and Trajtenberg (1995) as technologies that have a potential to affect a large part of the economy. We can think of energy systems, for example the technologies to use horsepower, fossil fuels, or nuclear power as source of energy. Such technologies had and have a large impact on pollution, for example in the context of the regional pollution of air and water. GPTs have been studied in endogenous growth literature in the context of Romer s variety expanding model (Helpman and Trajtenberg 1998) or models of growth based on inhouse R&D (Nahuis 2000). We model GPTs in the context of the quality ladder model (Grossman and Helpman 1991, Chapter 4). Note that two types of technical change play a role. Emissions per unit of output change when a new GPT is adopted; quality of final goods changes if a new product generation is introduced. Both adoption and quality improvements are costly and endogenous in the model.

Intrasectoral shifts and market structure dynamics affect pollution. Since it is costly to adopt new technologies, diffusion is slow and producers using old technologies may coexist with producers using new ones. Producers are heterogeneous in terms of pollution output ratios, prices and output levels. Changes in pollution result not only from changes in the pollution tax, but also from the process of creative destruction in which producers of one type are gradually replaced by producers of another type.

As our model has to include several technologies, different types of producers and different types of product qualities, the framework runs the risk of becoming very complex. To reduce complexity, we make a couple of simplifying assumptions. In particular, we set up the model such that only one type of innovation is being undertaken at a certain moment in time, either quality improvements, or new GPT adoption. Also, at most two types of firms are active at any point in time. In addition, we first describe the working of the model in an informal manner. Moreover, we present possible extensions complicating the model in a special section at the end.

The remainder of the paper is organised as follows. Section 2 presents the general mechanisms producing EKCs in our model. In section 3, the different time phases and acting firms are presented within a formal model. Section 4 discusses possible extensions and section 5 concludes.

2. An Informal Overview of the Model

In this section, we preview how the model generates a time pattern of pollution that first increases and then falls, that is, how it generates the environmental Kuznets curve. We distinguish four phases, which will be discussed first. Figure 1 summarizes the main features of the phases.

In the first phase, the so-called green phase , production uses a traditional general purpose technology (GPT) which causes no pollution.

In the second phase, a new GPT exogenously becomes available and is gradually (and endogenously) adopted in the economy. This new GPT allows production at lower labour cost than the traditional GPT. During adoption, pollution caused by firms using the new GPT is not yet known or, alternatively, not yet a public concern. Accordingly, we call this period the confidence phase . This phase can be divided into two subperiods. Initially, private research is used to invent the sector-specific complementary innovations that allow a specific sector to adopt the new labour-saving technology. Later, when all sectors in the economy have adopted the new GPT, research is redirected at improving existing product qualities.

The third phase starts after a considerable amount of information has been revealed that the new technology is harmful and after public concern has become widespread. It suddenly becomes evident that, during the confidence phase, pollution has steadily increased. From this point in time, the alarm phase begins. The government taxes emissions from producers that use the new GPT.

As soon as a new clean GPT becomes available, a new phase of adoption starts. We assume that this third GPT allows firms to reduce costs since it saves on pollution tax expenditures. With its invention, the cleaning-up phase starts. The clean GPT is gradually introduced in the different sectors of the economy and pollution decreases in the course of time. Again, initially research is used to adopt the new GPT during a first subphase; once the clean GPT has been fully adopted, however, research again switches and then exclusively aims at upgrading existing product varieties.

Neither technological breakthroughs nor environmental regulation are anticipated. New GPTs arise unexpectedly so that they do not affect agents forward-looking behaviour. Once available, however, private firms evaluate whether it is profitable to adopt a new GPT or not. Individual firms face uncertainty of being replaced in the market, but because the number of firms is large, this uncertainty washes out at the aggregate level. Households face no aggregate uncertainty in the economy and anticipate future changes in market structure. In particular, they predict how market structure and the rate of return to innovation evolve over time.

Firms engage in R&D either to improve the quality of a good or to adopt a new GPT. Both types of innovation result in creative destruction. Quality improvements drive producers with lower quality levels out of the market. Adoption drives producers exploiting the old technology out of the markets. Hence, innovation drives changes in market structure and it is crucial to understand what types of firms are active in which phases.

In the green phase, all incumbent firms use the traditional GPT so that, obviously, only quality improvement is possible. That is, research is exclusively aimed at upgrading of existing goods. Enterprises that produce these varieties are called traditional firms . The next GPT is assumed to enable cutting costs in the economy at a large scale, which is important to broaden industrial development in an early stage. Provided that the return on adopting the new GPT is larger than on improving product quality, research is fully directed at adoption activities in the first period of the confidence phase. Firms that have adopted this GPT are called labour-cost leaders and gradually replace traditional firms. When no traditional firms are left and the labour-saving technology is implemented in all sectors of the economy, researchers invent blueprints to upgrade goods qualities. Firms buying these blueprints replace the initial cost leaders. As there is no environmental regulation, we call the firms that supply higher qualities unregulated quality leaders .

In the alarm phase, unregulated quality leaders suddenly become regulated quality leaders as they are now taxed for their emissions. No clean GPT is yet available, but still, research is economically attractive. Thus in the alarm phase, research is again directed at upgrading of existing goods and improved qualities become available in the economy.

This changes when a new clean GPT arrives and innovators have an incentive to adopt. In this cleaning-up phase , the pollution tax induces adoption, since it causes the return on adoption to be larger than the return on quality upgrading. Firms that have adopted are called first movers . These firms gradually replace enterprises using the older labour-saving technology. Once all goods are produced with the clean technology, it is again quality uprading that is undertaken. As a consequence, new ecological quality leaders gradually spread over the whole range of supplied varieties.

What happens with pollution over time? In the green phase, there are no polluting activities. In the confidence phase, however, pollution increases and thus represents the upward sloping part of the EKC. Initially, pollution rises because of the increase in the number of cost leaders that implement the labour saving but polluting GPT. Even when this polluting technology has diffused over all sectors, pollution still increases but at a steadily decreasing pace. The reason for the rising but flattening time pattern of pollution is that cost leaders, which charge a high price and produce relatively small output, are replaced by quality leaders, which charge a lower price and produce and pollute more. Since over time less and less cost leaders are in the market, this replacement effect comes to an end and pollution stabilizes, which marks the end of the upward sloping part of the EKC.

In the meantime, information about the adverse effects of the pollutant accumulates and, at a certain moment, society imposes a tax on pollution, which marks the beginning of the alarm phase. Then, pollution already decreases in a discrete jump because industrial products become more expensive and demand is smaller due to the tax. Firms can only avoid pollution by producing less. As a consequence, more resources are used for research and less for current production. This is the beginning of the downward sloping part of the EKC. When a new clean GPT arrives, which starts the cleaning-up phase, steady reductions in pollution become feasible. In fact, the emissions that are caused by regulated quality leaders are gradually phased out in this period. When first movers serve all markets, pollution disappears from the economy. Growth is then characterized by the steady appearance of new ecological quality leaders.

Figure 1 shows the development of pollution over time and exhibits the three GPTs and the six types of acting firms in the four phases the economy is going through.

Insert Figure 1

3. The Model

3.1 Formal Overview

We first give a general overview of the model. We start from Grossman and Helpman (1991, Chapter 4) for the industrial structure of the economy, but we extend it to two types of innovation and we add pollution externalities.

There is a continuum of sectors, indexed *i,* each producing a good that enters the households utility function as an imperfect substitute. Each good can be produced in a number of varieties. Varieties differ in two dimensions. First, an unlimited number of different qualities of the same good can be produced. Second, the labour input requirements and pollution output ratios for a given quality level may differ according to the general technology adopted. If a new generation of the product is of higher quality, it provides l times as many services as the product of the generation before it. We refer to this type of technological development as quality improvements. It is the climbing of the quality ladder. The second type of technological progress is the switch to a production process belonging to a new general purpose technology. In sum, there are three dimensions of production: sector (i), quality (m) and (general purpose) technology (j). Innovation takes place in the latter two dimensions.

Both types of innovation are costly. Researchers target research in a certain sector to either develop a new quality or to develop the complementary innovations that allow implementation of a new GPT. Such a new GPT becomes available for adoption only at discrete times. Once a new technology becomes available, it can be potentially adopted in all sectors in the economy. Adoption requires a sunk cost (the development of the sector-specific blueprint) like innovation, and hence the rate of adoption (or diffusion of the GPT) is endogenous. Because adoption is costly, only innovations that allow a switch to lower production costs are adopted in equilibrium. Once a sector has switched to the new technology, quality improvements can be realized at the same cost as under the old GPT.

Competition among producers in the same sector results in the situation that only the producer with lowest production costs per unit of quality survives. This producer earns a profit that allows her to cover the cost of innovation or adoption.

Pollution hurts households utility. Whether a new technology causes pollution or not is unknown at the time of its introduction. Only when exposure to the pollutant has been long enough, damages, if any, can be established and an emission tax is implemented. This increase in production costs makes it attractive to switch to new production processes with lower pollution output ratios.

Households[4]

The representative consumer maximizes intertemporal utility given by:

$$U_0 = \int_0^{\infty} [\ln(C_t) - H_t] e^{-rt} dt \tag{1}$$

where ρ is the discount rate, *C* is the index of consumption, and *H* is harm from emissions, which consumers take as given. Consumers have Cobb Douglas preferences over a continuum of goods indexed *i* on the unit interval. Differentiated products of a given good *i* substitute perfectly for one another, once the appropriate adjustment is made for quality differences:

$$\ln C_t = \int_0^1 \ln\left(\sum_m q_{im} x_{imt} \right) di \tag{2}$$

where q_{im} is the quality of the *m*th generation of product in industry *i* and x_{imt} is the associated production at time *t*.

Maximization of utility subject to the usual budget constraints implies that only the good with lowest price per unit of quality is consumed in each industry *i*. We denote this good by $\tilde{m}_i$. Static utility maximization implies:

$$\begin{aligned} x_{imt} &= Y_t / p_{imt} && \text{for } m = \tilde{m}_i \\ x_{imt} &= 0 && \text{otherwise} \end{aligned} \tag{3}$$

[4] Households are modeled exactly as in Grossman and Helpman (1991), but for the inclusion of damages in the utility function.

where $Y_t \equiv \int_0^1 (\sum_m p_{imt} x_{imt}) di$ denotes total consumption expenditure.

Utility maximization also implies that consumption expenditure Y grows at a rate equal to the difference between the (nominal) interest rate r and the utility discount rate:

$$\dot{Y} / Y = r - r \ . \tag{4}$$

Production

Each producer holds a unique blueprint (patent) for production such that the market form is monopolistic competition. The blueprint allows the holder to produce good i at quality m, using technology j.

Unit production costs vary with technology but not with sector or quality. Production of one unit of output x requires a_{Lj} units of labour and emits a_{Zj} units of pollution if technology j is used. Unit costs c for technology j at time t are thus given by:

$$c_{jt} = a_{Lj} w_t + a_{Zj} t_t \tag{5}$$

where w and τ denote the wage and pollution tax respectively.

Output in each sector is given by:

$$x_i = Y/p_i, \tag{6}$$

that is spending per sector, Y (which equals aggregate spending because the total mass of sectors is normalized to one), divided by the price set by the incumbent in the sector, p_i.

Within a sector, firms engage in Bertrand competition. The leading firm sets the limit price that equals the cost level of its closest rival corrected for quality differences. It is useful to distinguish between two (broad) types of firms: cost leaders and quality leaders. Cost leaders are the first producers in the sector that have introduced a new general purpose technology. They have a cost advantage over their closest rival (but produce the same quality level). Cost leaders using technology j set a price equal to their rival s cost level c_{j-1}. Quality leaders are the producers that supply the highest quality level in the sector. They have a cost advantage over their closest rival in terms of costs corrected for the quality lead (but use the same technology). A quality leader using technology j sets the limit price $l\, c_j$, where $l > 1$ represents the quality difference. Since new blueprints for higher quality levels become available as a result of the innovation process (with the newest quality level being l times the previous quality level developed), quality leaders are always l ahead. This implies that we may write for the price set in sector i:

$$\begin{aligned} p_i &= l\, c_j && \text{if in } i \text{ a quality leader is active that employs technology } j, \\ p_i &= c_{j-1} && \text{if in } i \text{ a cost leader is active that employs technology } j. \end{aligned} \tag{7}$$

Corresponding profit levels are given by

$$p_i = \left(1 - \frac{1}{l}\right)Y \text{ if in } i \text{ a quality leader is active that employs technology } j,$$

$$p_i = \left(1 - \frac{c_j}{c_{j-1}}\right)Y \text{ if in } i \text{ a cost leader is active that employs technology } j. \tag{8}$$

Let us now be more specific and distinguish between the three GPTs and six types of producers already described above. The three GPTs appearing in the model are indexed j=1,2,3 for the traditional, labour-saving and clean technology respectively. GPT 1 and 3 require one unit of labour per unit of output and emissions are zero. GPT 2 requires $h < 1$ units of labour, but emits 1 unit of the pollutant per unit of output. Hence we may write:

$$a_{L1}=a_{L3}=1,\ a_{L2}=h,\ a_{Z1}=a_{Z3}=0,\ a_{Z2}=1. \tag{9}$$

In the green phase and in the confidence phase, there is no tax on pollution, that is τ=0, but from the alarm phase onward, emissions are taxed. The tax is assumed to be constant in terms of the wage, so we then have $t / w > 0$.

Six types of producers must be distinguished, depending on the technology used, whether they are cost leaders or quality leaders, and whether pollution is taxed or not. First, producers who supply the leading edge quality level of a good and employ the traditional technology (GPT 1) are called traditional firms , which we denote by subscript *T*. Second, producers who are the first in their sector to use the labour-saving technology (GPT 2) are called labour cost leaders , denoted by subscript *L*. Third, quality leaders using the labour-saving GPT active in the confidence phase are unregulated quality leaders , labelled by subscript *U*. Once pollution is taxed, the cost level of producers employing GPT 2 changes. Hence, quality leaders that are subject to the emission tax are to be distinguished as a fourth type of producers. They are labelled regulated quality leaders and denoted by subscript *R*. Fifth, firms that adopt the clean GPT 3 first are called first movers denoted by subscript *F* and, sixth, firms improving quality using GPT 3 are the ecological quality leaders with subscript *E*.

It is now straightforward to determine prices and profits of each type of producer from (7) and (8). Table 1 gives the results for producers of type *k*=*T, L, U, R, F, E*.

Table 1 Prices and profits for the six types of producers

k:	T	L	U	R	F	E
p_k:	lw	w	lhw	$l(hw+t)$	$hw+t$	lw
p_k:	$\left(1-\frac{1}{l}\right)Y$	$(1-h)Y$	$\left(1-\frac{1}{l}\right)Y$	$\left(1-\frac{1}{l}\right)Y$	$\left(1-\frac{1}{h+t/w}\right)Y$	$\left(1-\frac{1}{l}\right)Y$

Total employment in manufacturing, to be denoted by L_x, equals aggregate manufacturing output, which can be written as:

$$L_x = n_T \frac{Y}{lw} + n_L \frac{Y}{w}h + n_U \frac{Y}{lhw}h + n_R \frac{Y}{l(hw+t)}h + n_F \frac{Y}{hw+t} + n_E \frac{Y}{l(hw+t)} \tag{10}$$

where n_T, n_C, n_U, n_R, n_F, and n_E are the number of sectors with traditional firms, cost leaders, unregulated quality leaders, regulated quality leaders, first movers, and ecological quality leaders, respectively.

Total emissions are the sum of emissions of cost leaders, unregulated quality leaders, and regulated quality leaders. Aggregate pollution can be straightforwardly calculated as:

$$Z = n_L \frac{Y}{w} + n_U \frac{Y}{lhw} + n_R \frac{Y}{l(hw+t)} \tag{11}$$

Innovation

R&D aims at developing blueprints for improving the quality of a certain product or blueprints for incorporating the latest technology in a certain sector. The development of a blueprint requires a units of labour, so that the cost of a blueprint is aw. There are six types of blueprints corresponding to the six firm types. That is, there are blueprints for higher quality the traditional technology (denoted by T), blueprints for adopting the labour-saving GPT 2, denoted by L, and so on. We denote these blueprints as type k=T, L, U, R, F, E. The total amount of blueprints developed per period, or the research intensity[5], is:

$$i = \frac{1}{a}\sum_k L_{gk} , \tag{12}$$

where L_{gk} is the amount of labour engaged in developing blueprints of type k.

The value of a blueprint equals the stock market value of a firm that exploits the blueprint. Free entry in research guarantees that, whenever research activity is targeted at developing blueprints of type k=T, L, U, R, F, E, the value of a firm of type k equals the cost of the blueprint:

[5] Since the number of sectors is normalized to one, the number of blueprints developed equals the fraction of sectors in which innovation occurs.

$v_k \leq aw$ with equality whenever L_{gk}>0. (13)

The value of a firm is determined by the no arbitrage equation that states that the expected rate of return on stock must equal the return in an equal size investment in a riskless bond:

$$p_k + \dot{v}_k - s_k = rv_k \qquad (k = T, L, U, R, F, E) \tag{14}$$

where s_k is the expected value of the capital loss that occurs because of shocks to the sector. This capital loss crucially depends on what type of innovation is going on in the economy: whether it is quality innovation or adoption and which sectors innovation is aimed at. To solve the model, we only need to know the risk term for the type of firm for which new blueprints are developed. In the present model setup, only one type of blueprints is being developed at a certain point in time. Whenever quality improvements are being developed, quality leaders face the risk of being replaced by a new quality leader. They lose total value of the firm with a probability equal to the number of blueprints being developed: $s_k = iv_k$. However, when researchers develop blueprints to adopt the newest technology, cost leaders – firms that already have adopted the new technology – face no risk such that $s_k = 0$.

Labour market

Total labour is supplied inelastically and equal to L. Labour demand consists of employment in manufacturing and total employment in R&D.

$$L = L_x + \sum_k L_{gk} \tag{15}$$

3.2 Innovation and pollution in the green phase

In the starting phase, all active enterprises are traditional firms, that is, quality leaders using GPT 1. Innovation is aimed at improving product qualities within GPT 1. The rate of innovation is exactly the one known from Grossman/Helpman (chapter 4) and there is no pollution of the environment.

3.3 Innovation and pollution in the confidence phase

General equilibrium dynamics

The confidence phase is divided into two periods. In the first one, the *adoption subphase*, technology GPT 2 is available for adoption, but has not been implemented in all sectors. Adoption is costly, since only after developing the sector-specific blueprint at cost *aw*, a sector can use the new technology.

Adoption takes place only if the returns to this research investment are large enough.

Traditional quality leaders stay active as long as no rival in their sector has incurred the cost to adopt the new technology GPT 2. Innovators that do have adopted become labour-cost leaders. They are able to supply the same quality at a lower price. If research were targeted not only at adoption but also at quality improvement in traditional sectors, we would require $p_L = p_T$ for this to be an equilibrium, which only happens by coincidence. If $p_L < p_T$, no adoption would take place (L_{gC}=0), and the confidence phase would not start: the economy would remain in the starting phase without any effect of the arrival of a new GPT. We focus on the more interesting case in which $p_L > p_T$ so that adoption takes place without quality improvements in traditional sectors (L_{gT} = 0, L_{gL} > 0). Accordingly, we assume $h < 1/l$. As long as there are still sectors in which the new GPT 2 is not yet in use, all research is aimed at adoption and none at quality improvements because the former yields a higher return. Hence, once the new GPT becomes available, in the beginning all labour in R&D develops blueprints for adoption so that L_{gk} =0 for all $k \neq L$, $ai = L_{gL}$, and $L_{gL}+L_x=L$. The relevant state variable in this phase is the number of labour-cost leaders n_L, which starts at zero. It increases with the number of patents developed:

$$\dot{n}_L = i = \frac{1}{a}(L - L_x) \tag{16}$$

As noted above, with adoption only, cost leaders face no risk of being replaced as long as no quality improvements take place (s_L=0). Using (8), (13), and (14), we find the following no-arbitrage equation for adoption:

$$\left(1 - \frac{c_j}{c_{j-1}}\right)\frac{Y}{aw} + \frac{\dot{w}}{w} = r \tag{17}$$

Substituting (4) into (17) to eliminate r, substituting $c_j / c_{j-1} = h$, substituting (10) into (16) to eliminate L_x, and taking into account $n_T + n_L = 1$ and $n_U = n_R = n_F = n_E = 0$, we find:

$$\frac{\dot{y}}{y} = (1-h)\left(\frac{1}{a}\right)y - r \tag{18}$$

$$\dot{n}_L = \frac{L}{a} - y\left(\frac{1}{a}\right)\left[\frac{1}{l} - mn_L\right] \tag{19}$$

where $m = (1/l) - h > 0$ and $y=Y/w$. This system of differential equations in n_L and y characterizes the dynamics of the first period of the confidence phase. The resulting phase diagram is depicted in Figure 2 by the lower dy=0 locus and the curved path to the North East. The area above the $i=0$ locus is infeasible since it represents negative employment in R&D. For any point below this locus, innovation takes place, causing the number of quality leaders n_L to increase. The area to the right of the line n_L=1 is also infeasible since n_L represents a fraction of sectors, which cannot exceed unity.

Adoption comes necessarily to an end if all sectors have adopted the new GPT. It is clear from (18)-(19) that this will happen in finite time. In the diagram, it happens when the n_L=1 line or the $\dot{n}_L=0$ locus is hit. What exactly happens depends on the value y initially takes at the time that GPT 2 becomes available. At this time the confidence phase starts at n_L=0. Variable y has to jump initially such that the boundary conditions are satisfied. The endpoint is determined by the starting point of the subsequent improvement subphase. Since consumption is proportional to L_x and L_x is proportional to y (see (10)), consumption smoothing by households rules out a jump in y in the absence of unexpected shocks. Hence, the end condition for y in the adoption subphase is given by the initial value for y in the subsequent improvement subphase, which is determined below.

Insert Figure 2:
Dynamics confidence phase

In the second period of the confidence phase, the *improvement subphase*, all sectors have switched to the new GPT. As there is no further possibility to invent blueprints for adoption and because research is still economically attractive, inventions are now directed at improving product qualities so that L_{gk} =0 for all $k \neq U$, and $L_{gU}+L_x=L$. The rate of innovation can be expressed as:

$$i=\frac{1}{a}\left(L-L_x\right) \tag{20}$$

The rate of innovation now reflects the fraction of sectors in which a new quality leader replaces an incumbent. Since an innovator is indifferent between replacing a quality leader (firm of type U) or a cost leader (L-firm) – in both cases, profits equal $(1-1/l)Y$ – she spreads innovation effort equally over all sectors. As a result, a fraction n_L of the total number blueprints developed (i) hits L-firms, which are then replaced by quality leaders. Hence we have:

$$\dot{n}_L=-n_L i \tag{21}$$

At the same time, i is the probability for an individual quality leader that he will be replaced and will experience a complete capital loss. Hence, we have $s_U=iv_U$. Using (8), (13), and (14), we find the following no-arbitrage equation for quality improvements:

$$\left(1-\frac{1}{l}\right)\frac{Y}{aw}+\frac{\dot{w}}{w}-i=r \tag{22}$$

Substituting (4) into (22) to eliminate r, substituting (10) into (20) to eliminate L_x, and taking into account $n_L + n_U = 1$, $n_T = n_R = n_F = n_E = 0$, we find:

$$\frac{\dot{y}}{y}=\left(1-mn_L\right)\left(\frac{1}{a}\right)y-\left(\frac{L}{a}+r\right) \tag{23}$$

$$\frac{\dot{n}_L}{n_L}=\left[\frac{1}{l}-mn_L\right]\left(\frac{1}{a}\right)y-\frac{L}{a} \tag{24}$$

This dynamic system in the n_L, y plane characterizes the second period of the confidence phase. It is saddlepoint stable. Hence, starting at n_L=1, y jumps to the saddlepath and asymptotically converges to n_L=0 and $y = L + ar$. The path to the South West in Figure 2 depicts the dynamic adjustment.

Pollution and Innovation

During the confidence phase, untaxed emissions rise. This rise in pollution can be decomposed in a scale effect, technique effect and composition effect. First, the scale effect represents the change in pollution due to changes in aggregate production, holding sectoral production shares and pollution intensities constant. Second, the composition effect isolates changes in sectoral output shares due to changes in prices. Third, the technique effect represents the change in pollution due to changes in sectoral pollution intensities.

In the *adoption subphase*, pollution can be derived from (11) as:

$$Z = n_L y \tag{25}$$

Since both n_L and y gradually increase during the adoption subphase, we see immediately from (25) that the same holds for pollution. We argue that this happens because changes in scale, composition of demand, and technique all tend to increase pollution. First, the technique effect is positive (that is, pollution enhancing) because the number of sectors using the polluting technique increases over time (n_L rises). When a sector adopts the new GPT, it not only starts to pollute but also reduces prices and produces more. This accounts for a composition effect that increases pollution. Finally, total production affects pollution. Defining total production as the sum of sectoral production levels, we find the following expression for the confidence adoption subphase (from (6) and Table 1):

$$X \equiv \sum_k n_k x_k = y\left[\frac{1}{l}+\left(1-\frac{1}{l}\right)n_L\right] \tag{26}$$

Because n_L and y gradually increase during the adoption subphase, we see immediately from (26) that total production gradually rises, so that the scale effect also contributes to rising pollution levels.

To find out what happens to the rate of innovation, we need to know how L_x changes over time [see (16)]. The appendix shows that L_x increases (decreases) and innovation falls (rises) over time if h is large (small). The intuition is as follows. On the one hand, the rate of innovation tends to fall over time. This reflects the fact that the more sectors have switched, the fewer opportunities are left for further adoption and the sooner innovation has to be redirected to quality improvements, which yields a lower rate of return. Forward-looking behaviour of investors ensures that the rate of return is smoothed and research efforts are gradually reduced. With lower research efforts, labour becomes available to expand the scale of production. On the other hand, however, if production with the new GPT saves a lot of labour (that is, if h is small), the opposite happens and labour becomes available for research. In the latter case, the process of adoption is relatively fast and the scale of production as measured by L_x declines. Nevertheless, pollution increases over time since fast adoption allows the technique and composition effect to dominate the scale effect.

In the *improvement subphase*, pollution increases as well over time, although at a decreasing pace. Since all sectors are using GPT 2 with a fixed emission output ratio, changes in pollution can be explained entirely by changes in total output (X) or labour in production (L_x). From (10) and (11) we find:

$$Z = X = \frac{1}{h} L_x \tag{27}$$

The Appendix shows that L_x rises over time. It implies a gradual increase in pollution and a gradual fall in innovation. The underlying cause is a fall in the rate of return to innovation. As the proportion of low-price firms increases, more labour is allocated to incumbents and less is available per quality leader that replaces a cost-leader. As a result, profits for entrants fall and innovation becomes less profitable.

The innovation intensity at the end of the confidence phase (when n_L approaches zero) proofs to be:

$$i = \frac{l-1}{l}\frac{L}{a} - \frac{1}{l} r \equiv i_{GH} \tag{28}$$

Not surprisingly, this equals the innovation rate in the Grossman and Helpman (1991) model (denoted by i_{GH}).

3.4 Innovation and pollution in the alarm phase

The economy enters the alarm phase once it starts taxing pollution. Society is aware or alarmed about the polluting effects of production using GPT 2. To mitigate the adverse effects, firms are charged a pollution tax. Provided that all sectors are at least hit once during the second period of the adoption phase, all active firms in the alarm phase are regulated quality leaders (R-firms).

Because of the ongoing profit prospects, research is still active. Innovators develop new quality generations of the regulated products. Successful innovators become new quality leaders and set prices $p_R = l\,(h\,w + t\,)$. No other types of innovation are undertaken, so that $L_{gk} = 0$ for $k...R$ and $L_{gR}+L_x=L$. The value of a blueprint is determined by v_R, and we have $aw=v_R$ if $L_{gR}>0$. For simplicity we assume that the alarm phase starts only when the number of labour-cost leaders is negligibly small (n_L=0).

The dynamics of the alarm phase can be determined analogous to the dynamics of the improvement subphase of the confidence phase. Substituting (4) into (22) to eliminate r, substituting (10) into (20) to eliminate L_x, and taking into account $n_R = 1$, $n_k = 0$ for $k...R$, we find:

$$\frac{\dot{y}}{y} = y\frac{1}{a}\left(\frac{l-1}{l} + \frac{h}{l\,(h+t\,/\,w)}\right) - \left(\frac{L}{a} + r\right) \tag{29}$$

It is easy to see that, given a constant number of R-firms, y does not change over time either. Therefore, the dynamic system becomes one-dimensional in the alarm phase. Hence we can set (29) equal to zero to obtain the following expression for the steady state expenditures per wage income:

$$y = \frac{L + a\,r}{1 - q_{Z2}\,/\,l} \tag{30}$$

where $q_{Z2} = (t\,/\,w)/(h + t\,/\,w)$ is the share of pollution in total cost for GPT 2. In addition, the innovation growth rate in the alarm phase is readily calculated as:

$$i_{SSAlarm} = \frac{l}{l - (1 - q_{Z2})}\left[(\,l-1)\frac{L}{a} - \left(\frac{h}{h + t\,/\,w}\right)a\,r\right] \tag{31}$$

or, equivalently:

$$i_{SSAlarm} = \frac{l}{l - q_{Z2}}\left[i_{GH} + \frac{q_{Z2}}{l}\,r\right] \tag{32}$$

where i_{GH} denotes the steady state growth rate of Grossman/Helpman (1991, ch. 4), see (28). Note that spending per wage income and the rate of innovation increase in the pollution tax. The intuition behind this remarkable result for growth is that a pollution tax increases the cost of production relative to that of R&D, which is a non-polluting activity. Thus in the alarm phase, the rate of innovation increases and total emissions fall compared to the confidence phase.

3.5 Innovation and pollution in the cleaning-up phase

General equilibrium dynamics

From the point of view of GPTs, the cleaning-up phase is similar to the confidence phase. A new unregulated technology is available for adoption, but its diffusion takes time. Adoption is costly, since only after developing the sector-specific blueprint at cost *aw*, a sector can use the new technology. Adoption takes place only if the returns to this kind of research investment are large enough. To guarantee sufficient incentives to adopt we assume $l < t / w + h$, so that $p_R < p_F$ (see Table 1). Regulated quality leaders stay active as long as no rival in their sector has incurred the cost to adopt GPT 3. Innovators that produce with the new GPT are first movers (F-Firms).

We can use expressions derived for the confidence phase to find out the dynamics of the cleaning-up phase. For the adoption subphase, we need to replace n_L by n_F in (16). Substituting (4) into (17) to eliminate *r*, substituting $c_j / c_{j-1} = 1/(h + t / w)$, substituting (10) into (16) to eliminate L_x, and taking into account $n_R + n_F = 1$ and $n_T = n_L = n_U = n_E = 0$, we find:

$$\frac{\dot{y}}{y} = \left(1 - \frac{1}{h + t / w}\right)\left(\frac{1}{a}\right) y - r \tag{33}$$

$$\dot{n}_F = \frac{L}{a} - y\left(\frac{1}{a}\right) q_{L2}\left[\left(\frac{1}{h} - \frac{1}{l}\right) n_F + \frac{1}{l}\right] \tag{34}$$

where $q_{L2} = h /(h + t / w) = 1 - q_{Z2}$ is the labour cost share for GPT 2.

For the improvements subphase, we need to replace n_L by n_F in (21). Substituting (4) into (22) to eliminate *r*, substituting (10) into (20) to eliminate L_x, and taking into account $n_F + n_E = 1$, $n_T = n_L = n_U = n_R = 0$, we find:

$$\frac{\dot{y}}{y} = (1 - m_F n_F)\left(\frac{1}{a}\right) y - \left(\frac{L}{a} + r\right) \tag{35}$$

$$\hat{n}_F = \left[\frac{1}{l} - m_F n_F\right]\left(\frac{1}{a}\right) y - \frac{L}{a} \tag{36}$$

where $m_F = (1/ l) - 1/(h + t / w)$.

The two dynamic systems in (33)-(36) can be depicted in the n_F, y plane similar to Figure 2. The equilibrium dynamics can again be characterised by a rise in n_F from 0 to 1, while y increases. Then there is an endogenous switch to the improvement subphase in which both n_F and y fall over time.

Pollution and innovation
Pollution is obviously absent in the improvement subphase. Moreover, innovation falls similar to innovation in the improvement subphase of the confidence regime. Hence, we focus on what happens to pollution and innovation in the adoption subphase. Pollution is given by:

$$Z = y\left(\frac{1-n_F}{l\,(h+t\,/\,w)}\right) \tag{37}$$

It turns out that pollution continuously falls over time (see Appendix). More and more sectors switch to the clean technique (n_F increases), which reduces pollution. The upward pressures on pollution from increases in spending y are dominated by the technique effect.

Labour allocated to production can be written from (10) as:

$$L_x = y\left(\frac{(l-h)n_F + h}{l\,(h+t\,/\,w)}\right) \tag{38}$$

Since y and n_F increase over time, the amount of labour in production also gradually increases. Since the rate of innovation is negatively related to L_x, as in (16), innovation falls over time.

4. Extensions

This section discusses extensions to our theory on EKCs. A first additional feature is the determination of the income level where pollution starts to decrease. In reality the critical level of income at which pollution is de-linked from income differs greatly among different pollutants. Some pollutants are already almost completely phased out in rich economies (for example, CFCs), while for other pollutants we see only the upward sloping part of the EKC (CO2 for example).[6]

A related issue is the idea of overlapping EKCs. Booth (1998) has argued quite strongly that one pollutant can only be phased out because it is replaced by another pollutant. Put more moderately, it could be that seemingly clean GPTs turn out to be polluting in the end. If this is the case, additional GPTs have to be developed until, finally, one really turns out to be clean.

If there are several shifts during economic development, a further question would be the possible ability of individuals to expect the arrival of new GPTs, at least with a certain probability. It is conceivable that, for certain

[6] Of course, strictly speaking a monotonically increasing relationship between income and pollution is not an EKC by definition.

pollutants, technical solutions in the future can be anticipated to a certain degree. In other cases, however, it seems reasonable to assume that the arrival of a technological breakthrough is highly uncertain and arrives, if ever, unexpectedly.

In addition, the sequencing of the different phases can be more complex than modelled in this approach. Arrival dates of profitable GPTs and/or the introduction of taxes can be assumed to occur at different points in time so that more types of producers are active in the markets when a new phase begins.

Finally, one could elaborate more on optimal taxation. This requires the analysis of instruments to correct pollution, to correct R&D, and to correct output levels in order to remove the distortionary pricing effects. All these highly challenging issues are left for future research.

5. Conclusions

The model used in this paper shows that the existence of EKCs can conceivably be explained by a combination of public tax policy and different technology options. In particular, the gradual adoption of new general purpose technologies predicts a pattern of pollution over time that is consistent with the the upward and downward sloping parts of the EKC.

It should be noted that our model does not necessarily predict an EKC for all pollutants. In empirical research, the EKC is found only for specific pollutants. In the model, the downward sloping part of the EKC emerges only if the polluting GPT is replaced by a cleaner GPT. The adoption of the cleaner GPT requires sufficient incentives, a high pollution tax and low enough labour costs of the new GPT in particular. Otherwise, no technology shift takes place and the pollution tax only has the conventional static (level) effect. In addition, the further use of the dirty GPT without and with pollution taxes yields a realistic background to demonstrate the reasons for the turning point of the curve.

The framework has important policy implications. In the alarm phase, a pollution tax both lowers emissions and raises growth, a classical win-win situation. Moreover, the decline of pollution directly depends on the rate of adoption of the new clean GPT. Subsidies to increase the invention of adoption blueprints would be in favour of environmental quality. The optimum pollution tax rate and the optimality of subsidies for adoption activities depend on the weight of a clean environment in the utility function.

Appendix

A. Pollution and innovation in the confidence phase.

To find out the development of aggregate pollution and the rate of innovation in the confidence phase, we transform the phase diagram from Figure 2 and equations (18), (19), (23), (24) into a phase diagram in the L_x, n_L plane.

Adoption subphase

We show that L_x may either fall or rise during the adoption subphase, depending on whether h is small or large respectively.

From (10) we find the following expression for L_x in the confidence adoption subphase:

$$L_x = y\left(\frac{1-(1-lh)n_L}{l}\right) \tag{A.1}$$

We use (A.1) to replace y in (18) and (19) by L_x and find the following dynamic system for the adoption subphase:

$$\frac{\dot{L}_x}{L_x} = \frac{1}{a[1-(1-lh)n_L]}\{[l(1-h)+1-lh]L_x-(1-lh)L-[1-(1-lh)n_L]ar\} \tag{A.2}$$

$$\dot{n}_L = \frac{1}{a}(L-L_x) \tag{A.3}$$

The $\dot{L}_x = 0$ locus is downward sloping as long as $1/l > h$ which is the case due to our assumption that $m \equiv 1/l - h > 0$. The initial jump in L_x is determined in the same way as that of y, see main text: the endvalue of L_x is determined by its initial value in the subsequent improvement subphase. However, we can also use the endvalue of y to determine the end value of L_x by using the relation between these two variables given by (A.1). Hence, we can infer some useful properties of the endvalue of L_x from the endvalue of y. From Figure 1 or (18) we see that when n_L=1, y is bounded as follows:

$$y < \frac{1}{1-m}(L+ar) \tag{A.4}$$

Thus, from (A.1) we see that when n_L=1, L_x is bounded as follows:

$$L_x < \frac{h}{1-m}(L+ar) \tag{A.5}$$

From (A.2) we see that when n_L=1, we have

$$\dot{L}_x \leq 0 \text{ if } L_x \leq \frac{mL+har}{m+1-h} \tag{A.6}$$

Now consider the following condition:

$$\frac{h}{1-m}(L+ar) \leq \frac{mL+har}{m+1-h} \tag{A.7}$$

If condition (A.7) holds, L_x has to reach a value at the end of the adoption phase that turns out to be so small [namely smaller than the expression at the LHS of (A.7), see (A.5)] that it can only be reached by a declining L_x [as is revealed by (A.6)]. Note that for sufficiently low value of h this condition is satisfied. Figure 3c depicts this situation.

Let us now consider the opposite case in which h takes its maximal value, that is $h = 1/l$ so that $m = 0$. The dy=0 locus and the dL_x=0 locus are horizontal. Moreover, y and L_x have to reach the values $L+ar$ and $(L+ar)/l$ respectively at the end of the adoption subphase. Under our assumption that $i_{GH} > 0$, see (28), this endpoint lies above the dL_x=0 locus, see (A.2), and L_x has to increase over the entire adoption subphase. Figure 3a depicts this situation.

For intermediate values of h we get the dynamics as depicted in Figure 3b. The larger h, the more likely a rising pattern for L_x becomes. Note that L_x may first fall and then rise (but never the other way around) in the adoption subphase.

Improvement subphase

We show that L_x unambiguously falls during the improvement subphase.

For this subphase, we find from (10):

$$L_x = \left(\frac{1}{l} - mn_L\right)y \tag{A.8}$$

We use (A.8) to replace y in (23) and (24) by L_x and find the following dynamic system for the improvement subphase:

$$\frac{\dot{L}_x}{L_x} = \frac{1}{a[1/l - mn_L]}\{[1-2mn_L]L_x - [1/l - 2mn_L]L - [1/l - mn_L]ar\} \tag{A.9}$$

$$\frac{\dot{n}_L}{n_L} = -\frac{1}{a}(L - L_x) \tag{A.10}$$

The $\dot{L}_x = 0$ locus is downward sloping. Since the improvement subphase starts at n_L=1 and has to converge to n_L=0 and a constant, L_x has to start at a value above the dL_x=0 locus and will increase over time. Figure 3 combines the two subphases.

insert Figure 3

The development of pollution in the improvement subphase directly follows from (27) and the notion that L_x rises over time. The development of the rate of innovation is exactly the mirror of that of L_x, since $i = (L - L_x) / a$.

B. Pollution in the Cleaning-up phase.

We transform the dynamic system in (35)-(36) into a dynamic system in terms of Z and n_R. Substituting (37) in these equations to eliminate y, and replacing n_F by $1-n_R$, we find:

$$\frac{\dot{Z}}{Z} = \frac{(x - l / n_R)Z - L - a r n_R}{a n_R} \tag{A.11}$$

$$\frac{\dot{n}_R}{n_R} = -\frac{L - [l / n_R - (l - h)]Z}{a n_R} \tag{A.12}$$

where $x = h + l[t / w - (1-h)] - l$.

It should be noted that $[t / w - (1-h)] > l - 1 > 0$ from our assumptions made above to ensure adoption of the clean GPT. We now have two situations, depending on whether x is positive or negative. First, if it is positive, the dZ=0 locus slopes positive in the feasible region (for $0<n_R<1$) and the saddlepath slopes downward so that pollution unambiguously falls with the fall in n_R. Second, if x is negative, the dZ=0 locus has a vertical asymptote at $n_R = -l / x > 1$ and slopes downward in the feasible range (for $0<n_R<1$). However, the saddlepath slopes downward so that again pollution unambiguously falls with the fall in n_R.

References

Andreoni, J. and A. Levinson (2000), The Simple Analytics of the Environmental Kuznets Curve , *Journal of Public Economics* (forthcoming).

Booth, D.E. (1998), *The Environmental Consequences of Growth, steady-state economics as an alternative to ecological decline*, London and NewYork: Routledge.

Bresnahan, T.F. and M. Trajtenberg (1995), General Purpose Technologies Engines of Growth ? , *Journal of Econometrics*, 95, 83-108.

Bretschger, L. (1999), *Growth Theory and Sustainable Development*, Aldershot, UK: Edward Elgar.

Copeland, B. and S. Taylor (1994), North-South Trade and the Environment , *Quarterly Journal of Economics*, 109 (3), 755-787.

Cropper, M. & Griffiths, C. (1994): The interaction of population growth and environmental quality, *American Economic Review*, 84, 250-254.

de Bruyn, S. M. (1997). Explaining the environmental Kuznets curve: structural change and international agreements in reducing sulphur emissions, Environment and Development Economics, 2, 485-504.

de Bruyn, S. M (1999), *Economic Growth and the Environment*, Ph.D. thesis, Vrije Universiteit Amsterdam.

De Groot, H.L.F. (1999), Structural Change, Economic Growth and the Environmental Kuznets Curve , Ocfeb Research Memorandum 9911, Rotterdam University.

Grossman, G. M. and E. Helpman (1991), *Innovation and Growth in the Global Economy*, Cambridge Mass.: MIT Press.

Grossman, G. M. & Krueger, A. B. (1995), Economic growth and the environment , *Quarterly Journal of Economics*, 112, 353-378.

Helpman, E. and M. Trajtenberg (1998), A Time to Sow and a Time to Reap: growth based on general purpose technologies , in: E. Helpman (ed.) *General purpose technologies and economic growth*, Cambridge, Mass.: MIT press.

Nahuis, R. (2000), *Knowlwdge and Economic Growth*, Ph.D. thesis Tilburg University.

Selden, T. M., & Song, D. (1994): Environmental quality and development: Is there a Kuznets curve for air pollution? *Journal of Environmental Economics and Management* 27, 147-162.

Shafik, N. (1994): Economic development and environmental quality: an econometric analysis, Oxford Economic Papers, 46, 757-773.

Smulders, S. (1995) "Entropy, Environment and Endogenous Economic Growth", *Journal of International Tax and Public Finance* 2, 317-338.

Smulders, S. (1999) "Endogenous Growth Theory and the Environment", in J.C.J.M. van den Bergh (ed.) *Handbook of Environmental and Resource Economics*, chapter 42, 610-621, Cheltenham UK: Edward Elgar.

Stockey, N. (1998), Are there Limits to Economic Growth , *International Economic Review* 39, 1-31.

Torvanger, A. (1991), Manufacturing Sector Carbon Dioxide Emissions in nine OECD countries, 1973-1987: a divisia index decomposition to changes in fuel mix, emissions coefficients, industry structure, energy intensities and international structure , *Energy Economics* 13, 168-186.

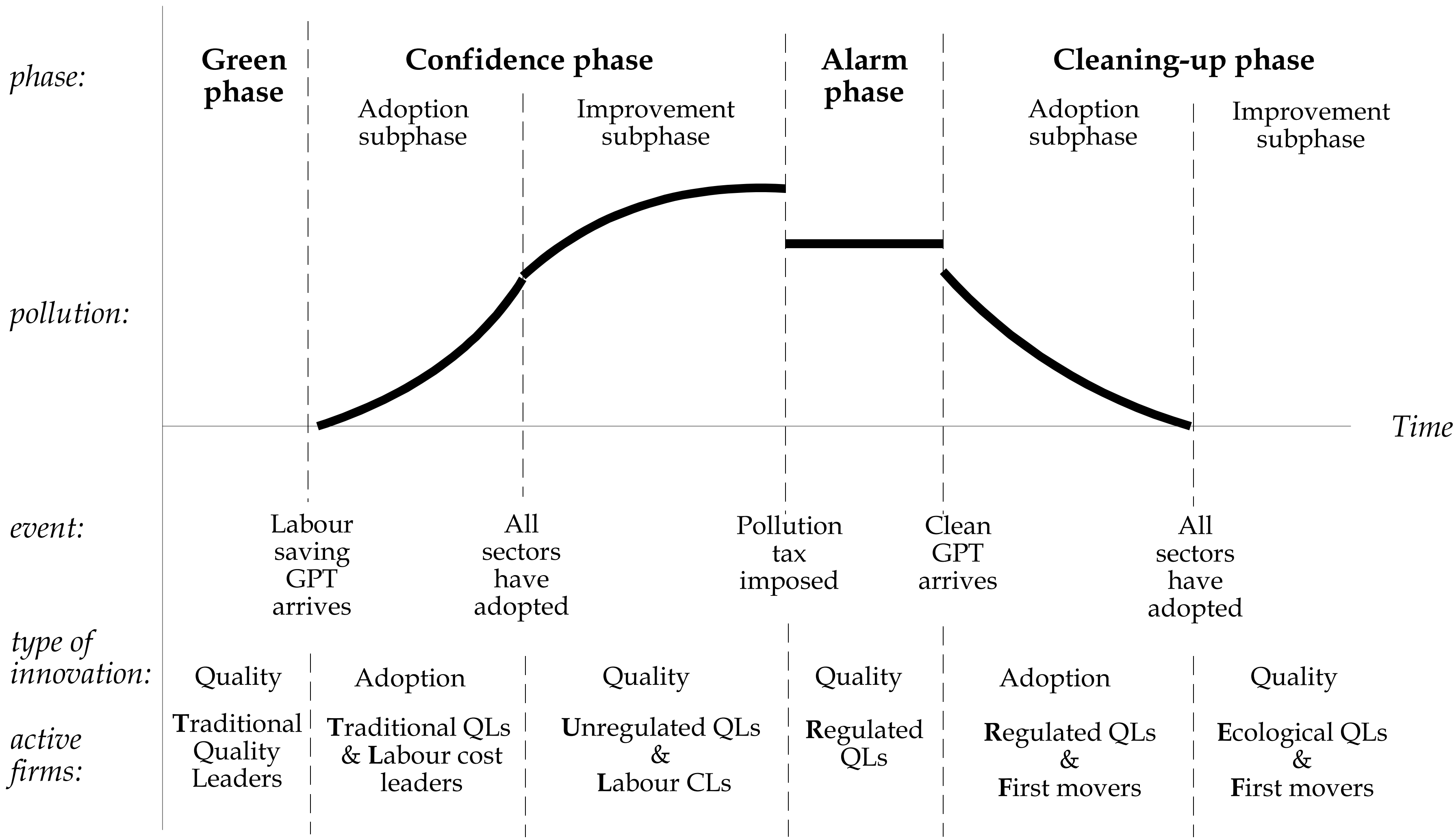


Figure 1 Overview of the model

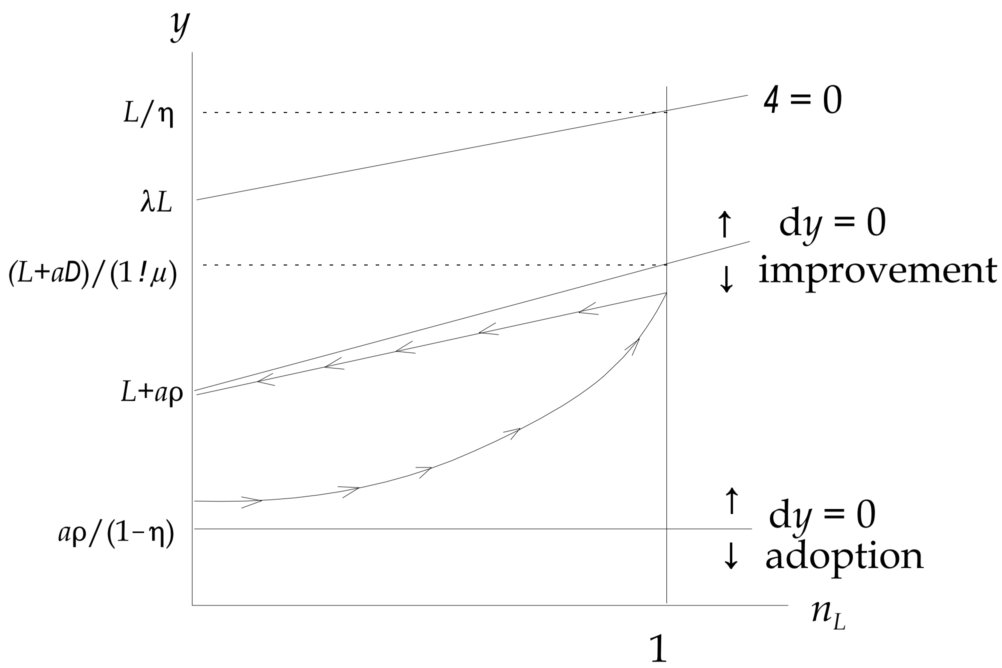
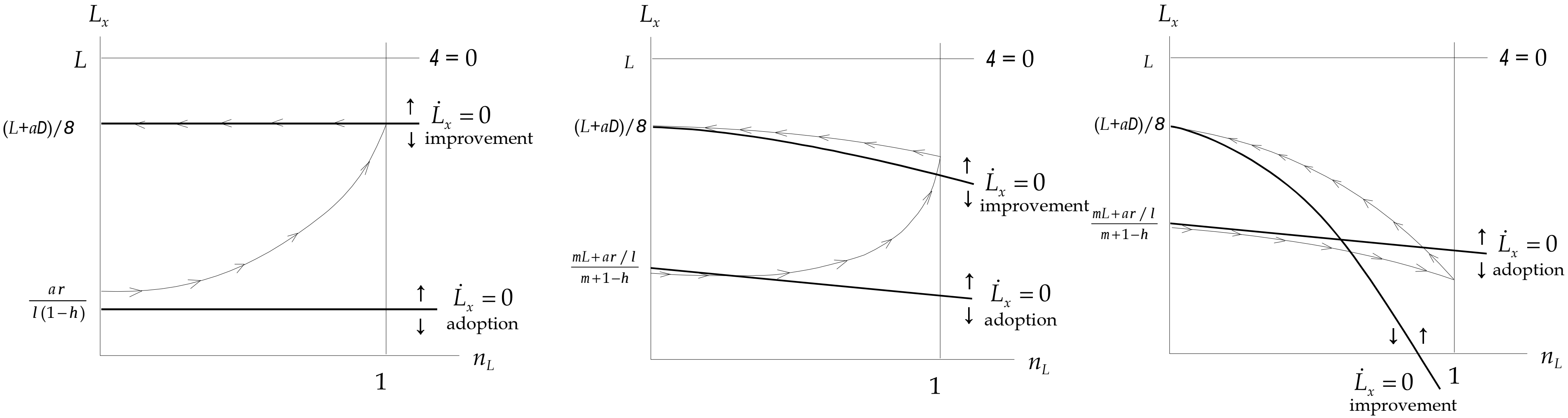


Figure 2 Dynamics Confidence Phase



a.η=1/λ (μ=0)

b. intermediate value for η (μ)

c. η small (μ close to 1/λ).

Figure 3 Dynamics Confidence Phase (n_L, L_x plane).